AN ABSTRACT OF THE THESIS OF

Steven Julius Paustian for the degree of Master of Science

in Forest Engineering presented on June 8, 1977

Title: THE SUSPENDED SEDIMENT REGIMES OF TWO SMALL STREAMS IN OREGON'S COAST RANGE

Abstract approved: Robert L. Beschta

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The protection of water quality and the maintenance of productive anadromous fisheries is a primary concern in the Pacific Northwest. Excessive suspended sediment loads is a principle water quality problem on small wildland watersheds in this region (Anderson, 1971; Brown, 1972). Man's activities have been shown to increase sedimentation rates in some cases (Burns, 1970; Megahan, 1972). However, more research is needed to define the basic sedimentation processes and factors before adequate assessments of man's impacts can be determined on a broad basis.

This paper presents the results of a study of the suspended sediment regimes for two small mountain watersheds located in Oregon's Coast Range. Suspended sediment concentrations in these kinds of watersheds are typically variable over short time spans. In-channel sources of fine sediment, particularly sediment stored in the bed gravels of armored stream segments, may be a major factor influencing the sediment regimes of these watersheds.

The primary objective of the study was to characterize the temporal variability in suspended sediment concentration on the two watersheds. In addition, nephelometric and gravimetric sampling procedures and the potential contributions of in-channel sources of suspended sediment were evaluated on the Oak Creek watershed.

The temporal variability in suspended sediment concentration during storm events and on a seasonal basis was determined using intensive automatic and manual sampling procedures. Sieve analysis of bed material composition and channel profile measurements were utilized to define the potential availability of suspendable material within the channel systems.

It was found that:

(1) Stream bed gravels are a significant potential source area of suspendable material.

(2) A decline in the suspended sediment concentration in the stream channel at a given flow occurs during the falling stage of individual runoff events and with successive events over the winter runoff season. This phenomenon can best be described as a flushing process, where the depletion of suspendable sediments may be associated with the successive release and capture of fine material by the bed armor layer.

(3) Sampling of sediment concentration did not appear to be significantly influenced by horizontal concentration gradients. However, vertical concentration gradients, particularly in

the transition zone between suspended load and bed load, did prove to be significant.

(4) Basic soils and geomorphic parameters provided useful indexes for comparing the sediment regimes of these watersheds.

The Suspended Sediment Regimes of Two Small Streams in Oregon's Coast Range

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed June 1977

Commencement June 1978

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Date thesis is presented June 8, 1977

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ACKNOWLEDGEMENTS

Funding for this study was provided by the Weyerhauser Corporation. I would like to express my gratitude to Tom Corbett for his invaluable help with data processing, Louis Klahn for his assistance with the instrumentation aspects of the study, Dr. George W. Brown and Dr. Peter C. Klingeman for their help in reviewing this paper. Special thanks to Dr. Robert L. Beschta for his guidance throughout the course of the study.

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THE SUSPENDED SEDIMENT REGIMES OF TWO SMALL STREAMS IN OREGON'S COAST RANGE

INTRODUCTION

The Oregon Coast Range is a region of abundant timber and fishery resources. As a result, this area is a major source of raw material for the nation's wood products industry. Studies in other areas have shown that sedimentation rates are often changed as a result of timber harvesting activities (Anderson, 1971; Megahan, 1972) and that excessive sediment production in streams can have adverse effects on various water uses. The detrimental effects of increased sedimentation to valuable anadromous fisheries is of major concern in Oregon's Coast Range, primarily because small forested watersheds are important fish spawning and rearing areas.

Timber yarding activities, road construction, and fires have been shown to be the major factors causing increased sediment production on wildland watersheds (Leaf, 1955; Anderson, 1971, Brown and Krygier, 1971). The steep topography and unstable soils found in much of the Coast Range make the problem of excessive stream sedimentation particularly acute.

Sedimentation processes have a significant effect on the hydrological and biological properties of a stream. The amount, type, and size of sediment entering and moving through a stream network has marked effects on the channel configuration and flow properties of the stream (Ackers, 1964; American Society of Civil Engineers (ASCE), 1971). The lower forms of stream biota (algae, bacteria, and invertebrates) rely on bank and bed substrates for shelter and as a source of food. In turn, these lesser organisms are essential to the food supply of fish. Streambed gravel interstices are important in fish reproduction as areas for spawning and incubation of eggs and as rearing habitat for young fry. The scouring of channel substrates by sediment laden water and the clogging of bed gravels by deposition of fine sediment particles can be detrimental to the stream biota. The physical damage of aquatic organisms, and the destruction of fish spawning and rearing areas has been attributed to excessive sediment loads in streams (Hollis, 1964; Burns, 1970). However, before the impacts of various land use practices on the sediment regime and biota of a small stream can be assessed, additional information on sediment transport processes is needed.

This study investigates certain aspects of sediment transport on two small forested watersheds in the Oregon Coast Range: the Oak Creek and Flynn Creek watersheds. These were chosen primarily because of existing stream gaging facilities and the availability of background data on streamflow and sediment yield from previous studies conducted at both sites. These watersheds are believed to be representative of the small forested watersheds in the area. This study was conducted between July, 1975 and April, 1977.

The objectives of this study are:

(1) To characterize the in-channel spatial and temporal variability in suspended sediment concentration at a single sampling station on each study watershed.

(2) To evaluate the applicability of gravimetric and nephlometric sampling and measurement procedures on these watersheds.

(3) To determine the potential contributions of in-channel sediment source areas to the suspended sediment loads of these streams.

(4) To compare suspended sediment concentration data from Oak Creek and Flynn Creek based on key watershed characteristics (soils and geomorphology).

LITERATURE REVIEW

Sedimentation Processes

Sedimentation can be described as a function of the following processes: detachment, entrainment, transport, and deposition. These processes are regulated by several watershed factors including climate, vegetation, soils, fluvial geomorphology and land use.

Raindrop impact has been found to be the primary cause of soil detachment (Mutchler and Young, 1975). The raindrop is also responsible for the initial movement of small soil particles. Rainsplash impact on an unprotected soil surface can weaken or break bonds between particles in the soil matrix. Once separated, these particles are carried short distances in a net downslope direction by rainsplash droplets. These detached particles are deposited directly into rills or onto interrill regions. Rills can be thought of as micro-stream channels, which have formed by the concentration of surface water. Interrill regions are characterized by a nearly uniform micro-topography. When the infiltration rate of the soil is exceeded by the precipitation delivery rate, thin films or sheets of water form in the interrill region. This water may then entrap detached soil particles and move them into the rill system, thus initiating the fluvial sediment transport process.

Once the sediment particles have entered the rill system, they begin a rapid downslope movement into larger rills, gullies, ephemeral stream channels, and finally the main stream channel system. Mutchler and Young (1975) have concluded that soil loss in a rill system is primarily determined by the supply of soil particles detached by raindrop impact. However, the erosion of soil particles by flowing water within the rill channel network is also an important detachment process.

Sediment transport in stream channel systems is an extremely complex and poorly understood process (ASCE, 1971). Three main categories are used to describe the transport process: suspended load, bed load, and saltation load. Suspended load is defined as all material that is carried in suspension by the water mass. Bed load is defined as all material that moves in partial or complete contact with the channel bottom. Bed load movement can be described as the sliding or rolling of particles along the channel bottom. A transition state exists between what is considered suspended load transport and that which is considered bed load transport. This phenomenon is sometimes referred to as saltation load. Sediment particles transported as saltation load may be suspended in the water for short periods of time, and either roll or bounce along the stream bed the remainder of the time. Total sediment load is the combination of bed load, suspended load and saltation load.

The mechanics of fluvial sediment transport involve interactions between the fluid, the sediment particles and the channel boundaries. Sediment particle size, density and shape greatly influence the transport process. Several indices are used as measures of these properties, including standard fall velocity, fall diameter, and sediment shape factor (Guy, 1970).

Fluid properties affecting transport include viscosity and density. In addition, hydraulic properties of the stream system (e.g. velocity gradients, hydraulic radii, water discharge and bed shear forces) also influence sediment transport in streams. Transport as suspended load is dependent on the transfer of momentum from the fluid to sediment particles. A state of equilibrium is reached when the supporting forces (shear stress and bouyant force) of the fluid equal the weight of the sediment particles in suspension. Suspended sediment transport is a dynamic process. Particles are constantly being transported upward by the water currents and eddies, while at the same time settling and deposition is occurring (Colby, 1963; Guy, 1970). No universal relationships have been developed to describe fluvial sediment transport, even under steady state conditions (steady flow rates, and constant input rates of sediment) in natural stream systems. The uncertainties related to turbulence and channel boundary effects have been the principle obstacles in this endeavor (ASCE, 1971; Cooper, Peterson, and Blench, 1972).

Sediment deposition occurs when the particle fall velocity exceeds the hydraulic lifting forces of the water. Deposition may occur very near the source in rills and interrill regions, or a considerable distance away in stream channels, lakes, reservoirs, or the ocean.

A certain amount of particle sorting is associated with the deposition process. The distinct grading and layering of sediment found in delta and reservoir deposits of large rivers illustrates the occurrence of sorting. Small streams show only a slight degree of particle sorting in bed deposits due to the wide temporal and spacial fluctuations in streamflow (Morisowa, 1968; Guy, 1970). Small streams do, however, exhibit a form of sorting called armoring (Milhous and Klingeman, 1973). The armor layer of a stream bed consists of a layer of large gravels or cobbles overlaying a finer textured matrix of sediments. The process of armor layer formation is not well understood. It is believed that the composition of the armor layer does change periodically and that this disturbance of the armor layer occurs during large storm flows (Milhous and Klingeman, 1973). Interstices between armor particles act as effective traps for fine suspended particles as they settle out of the water column during receding flows. These fine particles can later be released into the stream during high flows when the armor layer again breaks up.

Major Factors Affecting Sedimentation Processes

In natural stream systems, all of the sedimentation processes (detachment, entrainment, transport, and deposition) are at work during rainfall or snowmelt periods. The actions and interactions between these processes will vary greatly in time and space. Watershed climate, vegetation, soils, geomorphology, and land use are the major factors which cause this variability.

Precipitation provides the source of energy as well as the water medium for sediment transport processes. Therefore, climate is a primary factor in determining the hydrologic and sedimentation characteristics of a watershed. The amount, intensity, and distribution of precipitation on a watershed will greatly influence runoff patterns, streamflow characteristics, erosion, and sediment transport rates (Guy, 1970). The seasonal distribution and form of precipitation whether rain or snow can also be important. The effects of long-term climatic trends and extreme climatic events, such as droughts and floods, on sedimentation processes should also be considered. For example, the effects of extreme flood events have been observed to affect the sediment yields from a watershed for periods lasting several years after the event (Anderson, 1972).

Studies conducted on the Eel River by Brown and Ritter (1971) indicated increased sediment yields of 66% for a period of three years following the 1964-65 floods. In addition, climate influences erosion and sedimentation processes through its effects on vegetation and soil development.

Vegetation type and density are important factors in many erosion and sedimentation processes. Vegetation has a direct effect on soil stability through the binding of soil aggregates by plant roots. Plants also intercept precipitation, thus reducing raindrop impact at the soil surface. In addition, plants provide organic matter which protects the soil surface from raindrop impact and runoff and acts as a binding agent for soil aggregates. Old plant root canals provide macro-pores which can greatly increase soil infiltration rates.

The underlying geologic strata and the associated soil matrix of a watershed represent the source of fluvial sediment. The resistance of small soil aggregates or individual soil particles to displacement is partly dependent on the nature and strength of organic and inorganic constituents binding the soil particles. For example, a fine textured clay soil developed in a humid climate, under dense vegetation, will generally have a much greater resistance to erosion than a granitic soil developed under an arid climate. The chemical binding of clay minerals and the binding of soil aggregates by organic matter is responsible for the greater erosion resistance of the clay soil. Particle size arrangement and geometry also play important roles in erosion resistance. The interlocking of soil particles is the most important force resisting particle detachment in sandy or silty soils. Another aspect of erosion resistance is the role of particle aggregates in affecting the surface infiltration rate. The breakdown of surface soil aggregates by raindrop impact and the resulting sealing of surface pores effectively stops the transmission of water through the soil profile. The resulting increase in overland flow can then increase the rate of detachment of surface soil particles.

The geomorphology of a watershed has significant influences on sedimentation through hillslope and stream channel characteristics. The process of surface erosion as described by Mutchler and Young (1975) is affected by such landform factors as slope length, slope steepness and surface texture (Foster and Meyer, 1975).

The downslope movement of large soil masses by gravitational forces is a major contributor of sediments from hillslope sources. This process is particularly predominant in areas of steep topography. Several types of mass soil movement (soil creep, slumps, debris avalanches, earth flows) are described by Swanston and Swanson (1976). The angle of repose, and the makeup and orientation of soil and rock strata have a key role in determining amounts of sediment loading from these hillslope sources.

Stream channel morphology influences sediment detachment processes as well as transport rates. The scourings of the stream channel bed and bank, and the upslope extension of the stream channel can provide a major source of sediment. The stream also controls the rate of sediment transport by adjusting its channel dimensions and changing its channel gradient.

Guy (1970) and Anderson (1971) have presented discussions on the effects of site condition on erosion and sedimentation. In southern California, Anderson (1971) obtained the following information on the relative increases in sediment yield per unit area for logging: 25 times, fire 46 times, roads 50 times the normal surface erosion rate. Megahan (1972) has also studied the effects of logging and fire on sediment production in the Idaho Batholith Region. Megahan found that road related surface erosion in logged watersheds increased sediment yields 220 times over that measured on similar undisturbed watersheds in the same area. Megahan estimated that the actual timber harvesting operation (felling and skidding) increased sediment production by a factor of 1.6 over background levels.

Brown and Krygier (1971) studied the impacts of logging and slash treatment procedures on three small watersheds in the Alsea River basin. Their results show the greatest source of sediment from the logged watersheds was associated with the logging roads, although slash burning on the clearcut watershed, Needle Branch, did increase sediment production significantly. The burn was very hot and this was believed to have been a major factor in influencing the accelerated erosion rates. From these studies it can be concluded that land use activities are significant factors in determining the source and amounts of sediment delivered to a stream.

Measurement and Analysis of Fluvial Sediment

Sampling methodology and measurement procedures are two important considerations in sedimentation studies. First, in order to obtain representative values for various sediment parameters (sediment concentrations, transport rates) we need to be concerned with where, how many, how, and when samples should be taken. Secondly, standardized measurement procedures must also be followed in order to obtain accurate values.

Sampling Methodology

Sampling site location must be the first consideration. It should meet several basic criteria. The site must be representative of the flow and sediment conditions of the area being studied. The hydrologic conditions at the sampling site must remain fairly constant over the study period. The number of samples that need to be taken for a representative sample will depend on the specific site conditions. By comparing different frequencies of sampling, and various numbers of sampling cross sections an optimum sampling scheme can be found. This should result in the required precision with the least amount of expenditure (Porterfield, 1972).

The available types of sampling equipment are discussed in detail by Guy and Norman (1970). The overriding consideration in evaluating the effectiveness of sediment sampling equipment is that it should cause minimal disturbance of the flow velocity at the intake (Federal Interagency Work Group (FIWG), 1972). Due to the difference in densities of water and sediment, suspended sediment particles from the flow can occur when the water velocity changes. This separation can occur ". . . quite rapidly in the 0.06 mm or greater particle ranges" (FIWG, 1972). The merits of manual and automatic sampling also should be considered. Manual samples are the most accurate and can be used to evaluate the horizontal and vertical variability of sediment concentration in a stream. However, in monitoring small streams where changes in sediment loads are extreme and rapid, automatic sampling systems are often required (FIWG, 1972).

Most automatic systems collect point samples. In order to obtain representative results they must be calibrated using a number of manual hand samples. "The correlation coefficient and sampling efficiency are highest for the sediment fraction finer than 0.05 mm" and ". . .for the sediment fraction coarser than 0.2 mm, random errors usually are excessive" (FIWG, 1972, p. III-27). Fredriksen (1969), Bennett (1973), and Yorke (1976) present detailed descriptions of pumping sampler applications. Yorke believes that with proper installation, design, and maintenance pumping samplers will provide reliable results for 90% of the storms evaluated. He states that pumping samplers compared favorably with DH 48 samplers at all installations except during certain low flow events.

Horizontal and vertical velocity profiles result in some degree of segregation of the suspended sediment load within the stream channel. In most cases particles in the silt and clay size ranges can be assumed to be uniformly distributed in the water column. However, the concentration gradients of particles in the sand range 0.1 mm or greater have been shown to be much more variable (Guy and Norman, 1970). Generally these particles are transported near the stream bed. They are heavier and it is difficult for turbulent eddy currents to keep them in suspension. Colby (1964) has shown the ratio of mean stream velocity squared, divided by mean stream depth, closely defined the variability encountered in sampling different vertical stream sections. This relationship was developed further to include the effects of the percentage quantity of sand carried in the suspended load. A nomograph that relates V^2/D

(i.e., velocity squared divided by particle diameter), percent sand in the sediment load and percent maximum acceptable standard error, to the number of required sampling verticals, is presented in Guy and Norman (1970). The location of these sampling intervals must be determined. Guy and Norman describe two general procedures, normally used to account for horizontal sediment concentration gradients; the equal transit rate method and the equal discharge method. The goal of both methods is to obtain a composite sample that will account for the variation in discharge occurring across a channel.

The time of sampling is another factor that needs to be considered (Guy, 1970; Porterfield, 1972). Seasonal runoff trends should be considered in determining when to sample. The spring snowmelt season, and the heavy winter and spring precipitation events are the most critical periods for sediment transport in temperate regions. Summer thunderstorms are usually responsible for triggering flood events in arid regions. Hydrograph response characteristics such as duration and peakedness should be prime factors in selecting sampling timing and frequencies. Generally, a relatively large number of samples is desired on the rising limb of the hydrograph as compared to the falling limb.

The adequacy of previous sampling coverage for the watershed is another consideration. If a reliable sediment-discharge rating system has been developed for a watershed, only one or two samples near the hydrograph peak may be required to estimate sediment loads. The characteristics of the basin also need to be considered in a sampling scheme. If erratic storm patterns, heterogeneous soils and geology, or varied land use impacts are found within the drainage basin, a relatively elaborate sampling scheme should be considered. The accuracy and type of information that is required by the investigator to meet the study objectives should also influence sampling design criteria.

Measurement Procedures

The measurement procedures used to determine sediment concentrations can also affect the accuracy of results. Both direct and indirect measurements have been routinely applied in sedimentation studies. The analysis and interpretation of these measurements has led to several means of attempting to predict certain aspects of sedimentation phenomena. These predictive methods have been derived using theoretical, empirical and mathematical modeling approaches.

The direct measures of sediment concentrations are made by either filtration or evaporation techniques. These procedures are described in Standard Methods (American Public Health Association (APHA), 1975) and Recommended Methods for Water Data

Acquisition (FIWG, 1972). Direct measures are inherently the most accurate, but often require considerable time and expense to perform.

Indirect measurements of sediment concentrations are usually based upon the optical properties of sediment particles in a suspension. Turbidity is a non-technical term that has been used to describe a variety of conditions relating to the optical properties of a suspension. Ritter and Ott (1974) list three generally encountered definitions of turbidity: "a measure of light scattering or transmittance in a suspension, a reduction in water transparency, and an unclear or cloudy condition of water." Gibbs (1974) identified six major factors affecting the transmission of light through a suspension and the relative magnitudes of these effects. These are: dissolved material, 5%; the concentration of solid particles, 35%; the index of refraction, 10%; the shape of the material, 11%; the color of solids, 3%; and the size distribution of solid materials, 35%.

Instruments that are being used for turbidity measurements fall into two general categories; transmissometers and nephelometers. Transmissometry measures the transmission of light through a solution. Nephelometry measures the scattering of light, at a 90^{o} angle from a light source, by the particles in suspension. Unfortunately, these two types of measures respond differently to the factors discussed by Gibbs, and therefore are not directly comparable. Even specific types of instrumentation (e.g., nephelometers) are not directly comparable because of nonuniform design specifications and light sources. A national turbidity workshop (National Oceanograph Instrumentation Center (NOIC), 1974, p. 8) concluded the following about turbidity instrumentation:

> Instrument to instrument comparison may be possible if the necessary optical characteristics of the instruments are known and a scattering transfer standard or standards can be defined together with appropriate calibration procedures. For scattering instruments, the angle of measurement together with the size and shape of the optical beams and the scattering volume need to be specified as well as the spectral distribution of the energy utilized in the measurement.

From these examples it becomes clear that standardized measurement and calibration procedures, relatively homogeneous sediment characteristics, and clear definitions of the type of turbidity measurement applied are necessary to obtain accurate and reproducible determinations of sediment concentrations using indirect measurement techniques.

The applications of turbidity measurement to define sediment concentrations in natural waters has recently been attracting considerable attention. The principal reason for this interest is the recent enactment of federal water quality regulations which require the measurement of turbidity as a water quality index (Koeppen, 1974). Ritter and Ott (1974) have reviewed the results of several studies conducted by the USDI Geological Survey to determine the

the relationship between turbidity and suspended sediment concentration (SSC). Studies conducted on the Eel River (Brown and Ritter, 1971) found that a consistent relationship between turbidity and SSC did exist for individual sampling sites, but this relationship was different between sites. Another study on the Mad River showed a fairly consistent relationship between sediment concentration and turbidity existed throughout the basin (Brown, 1973). The amount of sand in transport was believed to be the primary reason for the variability between sampling sites. Since sand-sized particles have a smaller surface area per unit weight than silt or clay particles, sand can be expected to give lower turbidity readings for a given concentration value. A consistent relationship between turbidity and sediment concentration has also been found by Kunkle and Comer (1971) in a small Vermont stream. The implications of using indirect measurement techniques for determining suspended sediment concentration can be summarized as follows.

1. Turbidity-SSC relationships can usually be determined for individual basins.

2. No universal turbidity-SSC relationship exists today, because of the variability introduced by the widely different characteristics found between watersheds and the instruments used.

Prediction Techniques

Theoretical Techniques

Theoretical approaches have been widely used in attempts to explain and predict fluvial sedimentation processes. Lawson and O'Neill (1975) give a summary of basic hydraulic parameters which have been considered by theoretical researchers. These parameters include the following: velocity dynamics, characterized by the Froude Number; laminar and turbulent flow components, characterized by the Reynolds Number; the Chezy-Manning formulas as expressions of hydraulic energy gradients as a function of mean velocity; and the shearing forces exerted as the fluid interfaces, described by a tractive force equation. Several predictive relationships for bed material discharge (Shields, Duboys, Einstein, Meyer-Peter, and many other formulas) have been developed. Lawson and O'Neill conclude that ". . .the large range of variables encountered in the field has meant that no successful universal sediment discharge formula has been developed." Regarding the prediction of suspended loads, they state: ". . .Since the wash load material supplied to a stream is invariably less than the sediment transport capacity, equations of the type developed for bed material discharge are inappropriate." Suspended load concentrations are clearly more dependent upon the supply of material available for transport.

Cooper, Peterson and Blench (1972) have reviewed existing experimental results on sedimentation hydraulics and conclude that: (1) the scope of many of the individual experiments is extremely limited, and (2) experimental data are lacking for many possible flow conditions. Many of the semi-empirical relationships results in poor predictions for many of the natural stream flow regimes. Another approach to sediment transport prediction has been recently proposed by Yang (1972). Yang (1972, p. 1823) states:

> . . . it is doubtful a unique functional relationship between sediment discharge and the primary independent variables discharge, velocity and shear stress exists. These relationships may exist only under specific conditions. These conditions cannot be easily defined in the extremely complex environment of natural stream systems.

Yang's approach is to treat the stream system as a unit and describe its behavior using the potential energy status of the system as the primary independent variable. Yang's basic relationship is described by the following equation:

$$\frac{dz}{dt} = \frac{dx}{dt}\,\frac{dz}{dx}$$

where:

$\frac{dz}{dt}$ = stream power or the rate change of potential energy in the stream,

$\frac{dx}{dt}$ = the water flow velocity,

$\frac{dz}{dx}$ = the slope of the energy grade line.

Unit stream power as defined by Yang (1972) ". . .is the rate of potential energy expenditure per unit weight of water." He has developed a semi-empirical relationship between stream power and sediment transport rates. A comparison made between sediment and discharge data collected from several midwestern rivers, and the predicted values from the stream power and several other semi-empirical equations, demonstrated the stream power results to be the most highly correlated to the data (Yang, 1972).

Empirical Techniques

The direct long-term measurement of sediment loads is undoubtedly the best means we have of defining sedimentation processes in a watershed. This method is impractical for most applications, therefore several approaches have been utilized to estimate sedimentation rates based on limited amounts of data (Gottschalk, 1957). For example, sampling of sediment deposition in reservoirs can give useful information on annual sediment yield in an area. The sediment yield data obtained from monitored watersheds are often used to estimate sediment yields on nearby unmonitored watersheds with similar characteristics. However, the availability of such information is limited and no two watersheds can be expected to behave exactly alike.

The information obtained from detailed sedimentation studies has been used to derive empirical relationships between sedimentation processes and watershed characteristics (Hansen, 1966; Flaxman, 1975; Renfro, 1975). These relationships can then be used to predict sediment yields given a specific set of watershed conditions.

The development of regression equations relating sediment yields to several different watershed parameters has been widely used on small western watersheds. Hansen (1966) developed predictive relationships for sediment concentration on several small central Arizona watersheds using stream discharge and vegetative cover as independent variables. He found a reasonably accurate sediment-discharge rating curve could be defined for each distinct cover type on his study watersheds.

Hindall (1976) used a similar approach to develop a predictive equation for suspended sediment yields in five geographic provinces in Wisconsin. Some of the variables used in his analysis include drainage area, average discharge, flood runoff, channel slope, channel length, a vegetative cover index, a soil index, and a precipitation-intensity index. Flaxman (1975) presented a simple regression equation for evaluation of sediment yield in western streams:

$$Y = a X^m$$

where:

Y = sediment concentration in mg/l,

X = discharge in ft^3/sec,

a and m = constants.

He assigns different exponential values to streams which fall into certain sediment source area classes. Flaxman's approach has very broad applications; however, a large degree of predictive accuracy is consequently sacrificed.

Another widely used empirical approach for prediction of sediment yields is that of soil loss determinations and sediment delivery ratios. This method attempts to estimate the gross surface erosion from a hillslope area and to predict the relative amounts of this material that are actually transported past a fixed point in a given amount of time. Renfro (1975) discusses how this method is used by the Soil Conservation Service in their studies: gross erosion is calculated using the universal soil loss equation for surface erosion along with surveys of channels, gullies, and road cuts to determine average erosion losses from these sources. He lists several parameters, including sediment sources, magnitude and proximity to stream channels, channel form, sediment texture, depositional area, drainage area, channel density, and relief-length ratio as being the major factors influencing sediment delivery ratios.

Hadley and Shown (1976) give qualitative evidence showing the importance of stream channel characteristics, land form features, and flood plain development in determining the conveyance rate or delivery of sediment for several small watersheds in Wyoming and

Colorado. They conclude that a major problem in applying the delivery ratio approach is the difficulty in obtaining reliable information on sediment sources.

Road construction has been singled out as the principal erosion and sedimentation problem on forested lands (Brown and Krygier, 1971; Megahan, 1972; Anderson, 1974). Megahan (1974) has proposed an empirical model to describe the time trends of erosion following forest road construction. Leaf (1974) has modified this equation to determine a predictive relationship for the delivery of this sediment to the stream system.

Modeling Techniques

Modeling has been the third basic approach applied to sediment prediction. Modeling requires a simplification of natural erosion and sedimentation processes so that they can be described mathematically. These processes can then be simulated on a digital computer. Given a certain amount of information on the watershed's hydrologic parameters, the computer model can be used to predict sediment yields, transport rates and delivery ratios of the stream. The Stanford Watershed and Sediment Model represents a lumped parameter model capable of generating this type of information. However, extensive field data are generally required for calibration of such a model (Lawson and O'Neill, 1975). A difficulty arises where watershed modifications such as changes in land use occur.

Modelers have found it useful to divide erosion and sedimentation processes into an upland phase and an in-channel phase. Some approaches to modeling upland erosional processes are described by Meyer, Foster, and Romkens (1975) and Foster and Meyer (1975). Their model is based on fundamental erosion mechanics and includes such factors as soil rilling, slope length, slope steepness and surface cover. They believe that the method has the "potential" for describing erosion and deposition at any point in time or space.

The approaches for modeling in-channel sediment transport are generally closely related to streamflow modeling efforts. Holton, Yen, and Comer (1975) discuss the application of the USDAHL Model of Watershed Hydrology and the Three-Tube Model of Flood Routing to sediment transport phenomena. These models use several parameters including overland flow, infiltration, and evapotranspiration to predict storm hydrographs and water routing in a drainage system. It is hoped that a sediment transport component can be integrated into these models. The modeling approach to sediment transport is in its infancy. However, reliable results from and practical applications of these techniques are expedted in the near future (Fleming, 1975).

WATERSHED CHARACTERISTICS

Both study watersheds are located in the central portion of the Oregon Coast Range. The Oak Creek watershed is located in the McDonald Forest, 11 km northwest of Corvallis, Oregon, and is managed by the School of Forestry, Oregon State University (Figure 1). The Flynn Creek watershed is located about 1 km southeast of Toledo, Oregon in the Alsea River basin and is within the protection boundaries of the Siuslaw National Forest (Figure 2).

The climate at both sites is a marine type, characteristically having warm, dry summers and cool, wet winters. Annual precipitation averages 230 cm at Flynn Creek and 150 cm at Oak Creek. The majority of the precipitation (60%) occurs between November and February. Most of the winter stream freshets occur during this time. Snowfall in the region is light and any accumulations of snow on the ground last for only a few days. The storm patterns in the area are greatly influenced by the coastal mountains. Therefore, precipitation amounts and intensities for a given storm can vary appreciably within a watershed and between watersheds.

Both basins are densely forested with 100 to 200 year old timber, Douglas-fir (*Pseudotsuga menziesii*) and western red cedar (*Thuja plicata*) being the principal species found on the uplands, and Oregon white oak (*Quercus garryana*), red alder (*Alnus rubra*), and

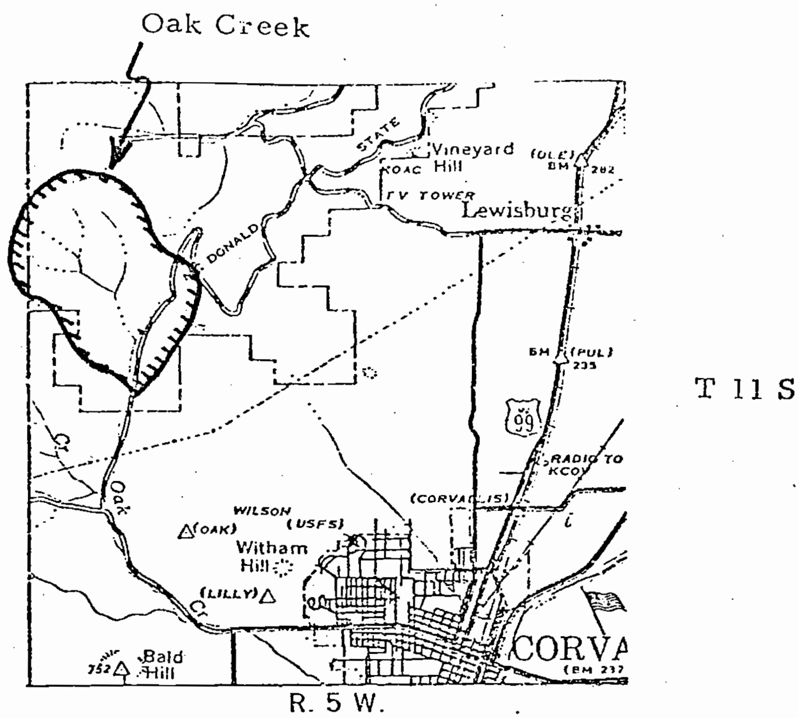


Figure 1. Location of the Oak Creek study site near Corvallis, Oregon.

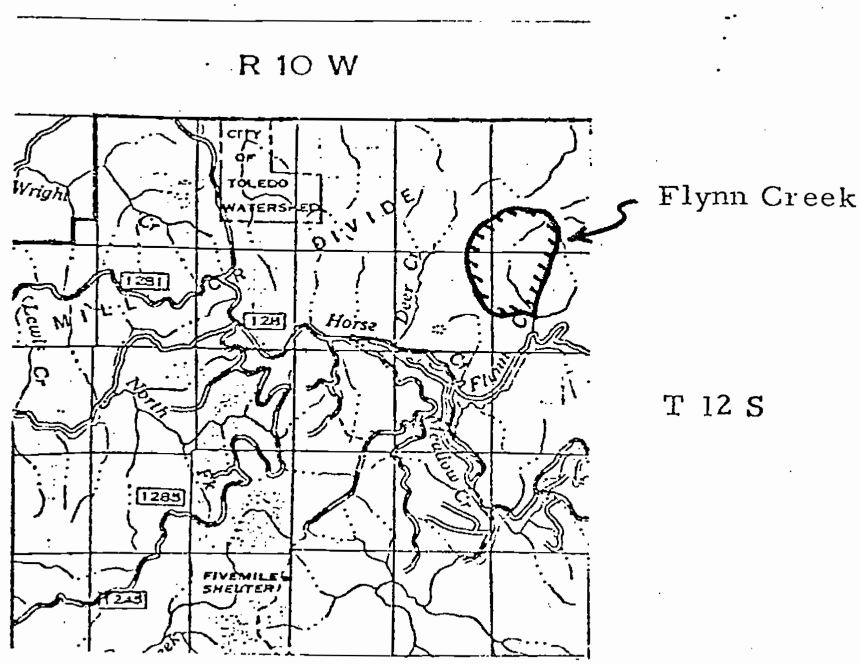


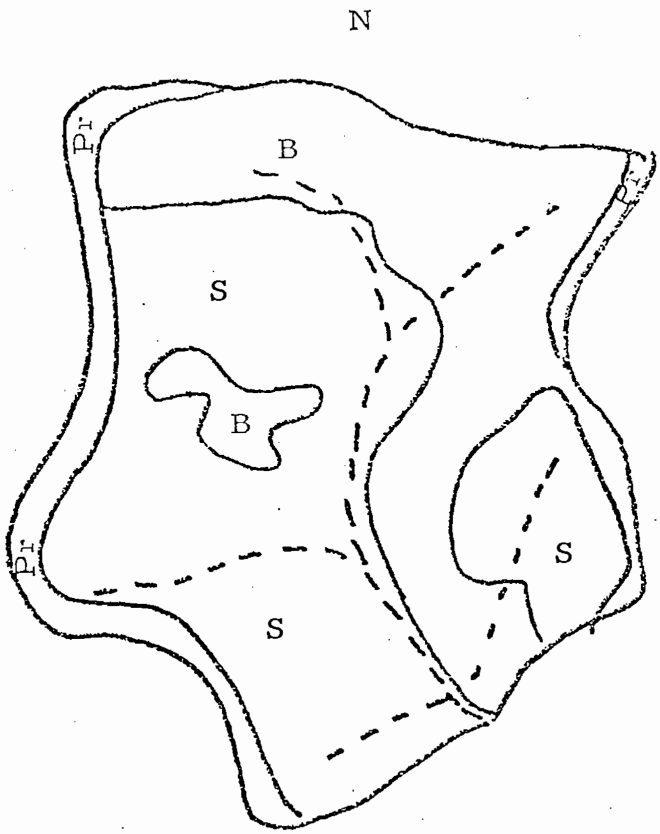
Figure 2. Location of the Flynn Creek study site approximately 16 km southeast of Toledo, Oregon.

bigleaf maple (Acer macrophyllum) making up the majority of the species growing along the stream channels. Minor tree species include western hemlock and Oregon ash. The understory vegetation of Oak Creek consists of bracken fern, blackberry, snowberry, and poison oak. The understory vegetation of Flynn Creek includes vine maple, salal, swordfern, and salmonberry. Several varieties of perennial grasses have become established on some of the dry valley bottom areas. This is also true of several upland areas on Oak Creek where the regeneration of old cut-over units was severely inhibited by droughty site conditions during the summer.

Flynn Creek is an important spawning stream for anadromous fish and is tributary to the Alsea River, a major fishery in the Pacific Northwest. The species of major importance are coho salmon, sea-run cutthroat trout and steelhead trout (Moring, 1975).

Oak Creek is part of the Mary's River drainage system. In contrast to Flynn Creek, it is of negligible importance from an anadromous fisheries standpoint.

The entire Flynn Creek watershed is located on an area of sandstone substrata known as the Tyee Formation. Soils developed from this parent material belong to the Bohannon, Slickrock, and Preacher Soil Series (Figure 3). The genesis of these soil types was primarily influenced by variations in topographic relief (USDA, 1973). The watershed area is 202 ha and ranges in elevation from



Legend

Stream course: -----
Scale: 1 cm = 0.2 km
Pr = Preacher Soils Series
B = Bohannon Soils Series
S = Slickrock Soil Series

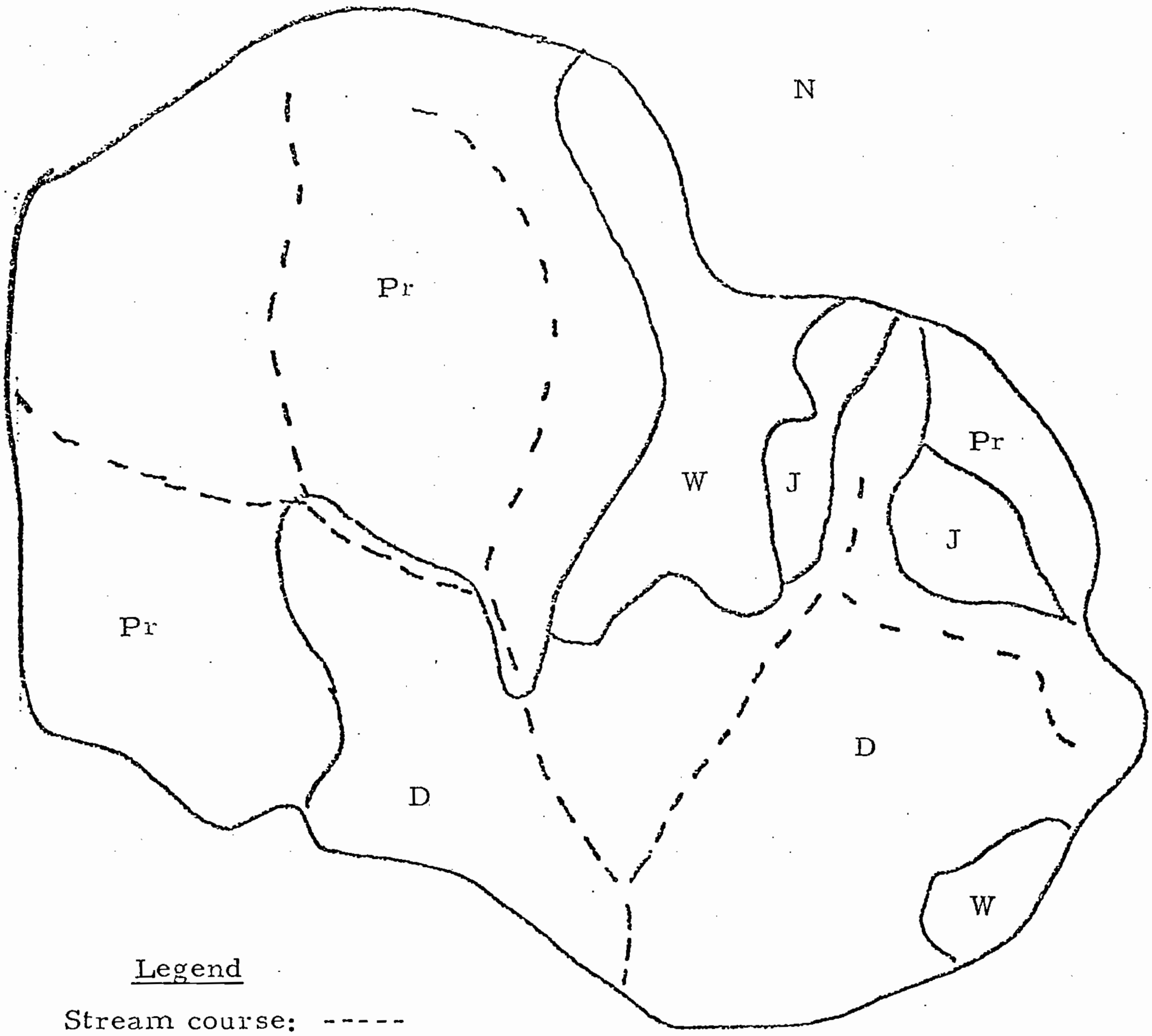
Figure 3. Major soil series for the Flynn Creek watershed (adapted from the Alsea Area Soil Survey, USDA, 1973).

183 to 396 m. Total stream length is approximately 1,433 m. Average summer depth of the mainstem of Flynn Creek is 13 cm and the average width is 1.74 m (Moring, 1975). The stream gradient on the main channel of Flynn Creek is relatively gentle, averaging 0.03 to 0.04 $m \cdot m^{-1}$ (Figure 4). The valley narrows to a few tens of meters approximately 300 m above the stream gage.

Figure 4. A typical channel section on the mainstem of Flynn Creek.

The stream channel in this 50 m segment has cut down to bedrock, and has attained a steeper gradient relative to the rest of the main channel. Above this point the valley widens and the stream gradient once again becomes shallow. The valley bottom in this area is comprised of large fluvial gravel deposits some of which are trapped behind large organic debris. The first and second order channels, which have delivered much of this material to the main channel, can best be characterized as steep bedrock chutes. The large sediment deposits along the main channel are apparently the result of past mass soil movements at the headwaters of the small tributaries. The channel banks are, characteristically, 0.5 m in height and slightly undercut around bends. Except in bedrock areas the channel width is influenced by thick growths of alder, vine maple, and salmonberry, whose roots help to bind the bank material. Gravel bars are a common bed feature, particularly point bars at channel meanders. The bed material consists of an armor layer of small sandstone cobbles 1 to 5 cm in diameter, overlaying a mixture of gravel and sand size particles. This material is very friable and can be broken up easily in the hand.

The Oak Creek watershed is located within the Marys Peak Intrusion Formation. Bedrock is comprised of basalts which have been weathered into clay-loam soils. The major soil types in the watershed are the Dixonville, Price-Ritner, and Jory Soil Series (Figure 5). The watershed area is approximately 751 ha, and ranges in elevation from 146 m at the gaging station to 664 m at the watershed divide (Figure 6). Stream length is about 2900 m. Average summer depth on the main branch varies from 10 cm in riffles to 1 m in pools. Average channel width is 4 m on the main



Legend

Stream course: - - - - -
Scale: 1 cm = 0.2 km
W = Witzel Soil Series
Pr = Price-Ritner Soil Series
J = Jory Soil Series
D = Dixonville Soil Series

Figure 5. Major soil series of the Oak Creek watershed (adapted from the Benton County Soil Survey, USDA, 1975).

Figure 6. View of the Oak Creek watershed looking south toward Corvallis.

branch and 3.5 m on the upstream channels. Channel gradient is low on the main section (0.04 $m \cdot m^{-1}$) and increases gradually to 0.08 $m \cdot m^{-1}$ on second order channels, reaching a maximum of 0.24 $m \cdot m^{-1}$ on the small headwater tributaries. The main channel along the lower portion of the watershed lies in a broad grass- and tree-covered valley. Here the stream follows a basic pool-riffle sequence with a slight amount of meandering. The channel banks are steep, generally 0.3 to 2.0 m deep with moderate amounts of undercutting evident at meanders (Figure 7).

Figure 7. Typical channel segment on the mainstem of Oak Creek.

Alder, bigleaf maple, vine maple, and other brushy species play an important role in binding the fine textured bank material and reducing bank cutting. Large volumes of gravel and cobbles have been deposited behind natural debris dams, particularly along the lower channel reaches. Large deposits of gravel also occur as point bars. The upper channel reaches have been deeply incised. This is evident on portions of the West Fork of Oak Creek where the channel morphology resembles that of a gully system. There is also a distinct lack of large cobbles, debris dams, and root wads that could act as stabilizing influences. Large bank scarps of 3 m in height are not uncommon.

Several mass failures have contributed material to the upland stream channels in the past. The majority of these slides occurred in 1964 and have since been largely stabilized by vegetative cover.[1] The bed material in Oak Creek also exhibits armoring (Figure 7). The size of the armor layer is highly variable ranging from 8 cm diameter cobbles to gravel sized particles. The underlaying material is a heterogeneous mixture of gravel, sand, silt, and clay size particles.

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[1]Personal communication, Marvin Rowley, Manager, McDonald School Forest, 1975.

METHODS

Measurement Procedures

A general ground reconnaissance of both watersheds was made during the summers of 1975 and 1976. Observations were made on cover density, the location of unstable channel sections, areas of landslide activity, the influence of road drainage installations on the streams, the frequency and location of large debris accumulations, and general channel morphologic characteristics. A detailed topographic map of McDonald Forest, scale 1:4800, was used to determine geomorphic parameters such as stream number, drainage density, mean channel length, and channel gradients for Oak Creek. Many of the morphological parameters for Flynn Creek were obtained from a USDA Forest Service enlargement of the USDI Geological Survey, Toledo Quadrangle (map scale 1:62500). Additional information on Flynn Creek was obtained from data on the Alsea Watershed Study (Moring, 1975). Soils information was derived from the Alsea Area and the Benton County Area soil surveys (USDA, 1973, 1975).

Channel stability measurements were taken to determine the average annual depth of scour and backfill of bed gravels at selected channel sections in the two watersheds. Twelve channel stability stations were established on the Oak Creek watershed, five on the main Oak Creek channel and the remainder on the East and West Fork tributaries. Each station was marked by yellow pipes driven into opposite stream banks. Cross-sectional profiles of the channel were determined by measuring the vertical distance from the stream bed to a tape stretched between the two pipes. Heights were measured to the nearest 0.003 m at intervals of 0.3 m across the channel. The approximate distance between stations was 20 to 30 m on the West Fork whereas a spacing of 7 m was used for the five stations located on the mainstem of Oak Creek. Scour chains were placed in the bed gravels to a depth of approximately 0.8 m with a portion of the trailer left above the surface. Three to four scour chains were placed at equally spaced intervals across the channel. The scour chains were placed during the summer of 1975 and remeasured the following summer. These measurements were used to estimate the depth of scour and backfill that had occurred during the winter period. The same procedures were followed in the location and measurement of profiles, scour and backfill on Flynn Creek. The Flynn Creek stations were located upstream from the gaging station, and were spaced at 4 m intervals.

Bed composition measurements were used to obtain an estimate of fine sediment storage in the bed gravels. The samples were taken during low flows in September of 1976 from dry gravel bars that are normally well below the water level during the winter months.

A total of four samples was collected from the main channel of each stream by imbedding a 20 cm diameter cylinder approximately 10 cm into the bed gravels. The bed material was then removed from the inside of the container and resulted in a sample volume of about 3000 cm^3. The fine suspendable material was separated from bed material samples by wet sieving through a no. 200 US Standard Sieve (75 mm). Two subsamples were taken from this mixture, and analyzed using the standard procedures for determining total filterable residue (APHA, 1975).

Two instruments were used in this study to collect samples for laboratory analysis of suspended sediment concentration and turbidity. The majority of the samples were taken with the Instrument Specialties Company (ISCO) Automatic Pumping Sampler. Additional samples were taken with the DH 48 hand-held depth integrating sampler (Inter-agency Committee on Water Resources, 1965).

The ISCO Model 1392 Pumping Sampler (Figure 8) is capable of collecting a total of 28 discrete samples at intervals between 0.5 to 6 hours. A maximum of four composite samples can be taken for each bottle. The sampler intake (Figure 9) at the Oak Creek site was attached to the end of a steel pipe which is anchored by a metal hinge to a foot bridge. The end of the pipe is bent at an angle roughly parallel to the flow direction, thus minimizing the separation of flow

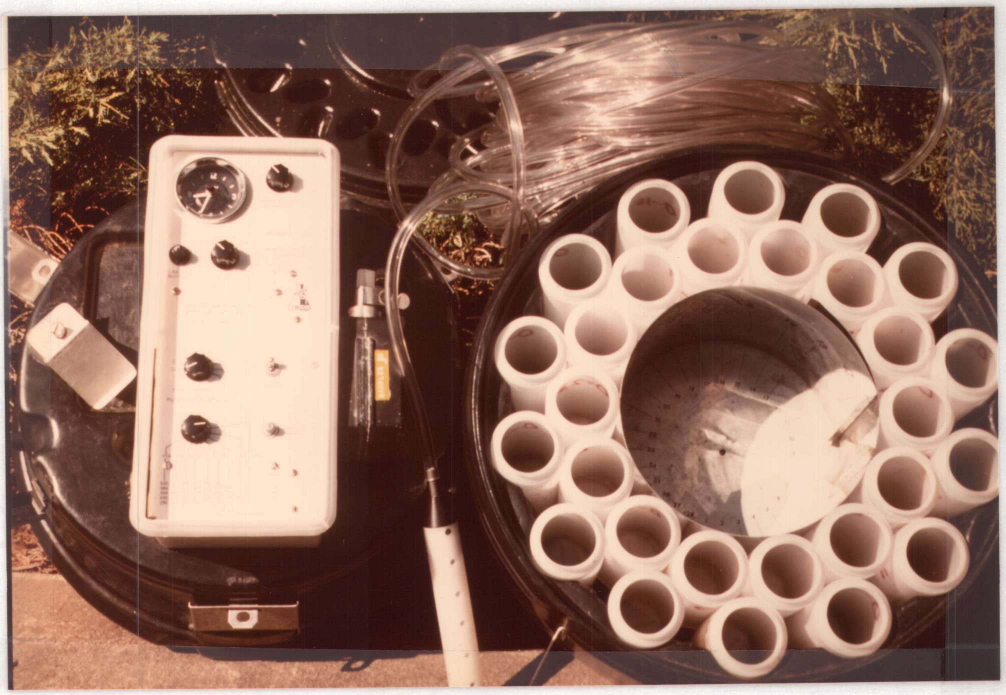

Figure 8. The ISCO Model 1392 Automatic Pumping Sampler.

Figure 9. The ISCO intake, in position at Oak Creek.

around the intake nozzle. This arrangement is particularly effective in reducing the clogging of the intake by leaves and twigs. It also allows large debris to pass, thus protecting the intake nozzle and tubing from damage or from being dislodged. During low flow, the intake nozzle rests on the concrete bed of the flume. At most of the higher storm flows, the drag forces exerted by the water on the pipe suspends the intake a few centimeters from the bed. The intake at Flynn Creek was located in the plunge pool directly downstream of the stream gaging weir. The nozzle was suspended approximately 0.5 m above the channel bottom.

During the winter of 1975-76 the ISCO samplers were operated on a continuous basis from October through April. Sampling occurred every two hours, with three discrete samples combined to make one composite sample. During storm events, when an operator was present, the sampling frequency and the number of discrete samples were increased. A sampling interval of 0.5 to 1 hour and one sample per bottle was generally used. The resolution of some of the wide-interval samples was found inadequate, particularly on the rising limb of very peaked storms. In addition, it was found that no measurable quantities of sediment were being transported between storm events and thus the continuous operation of the pumping samplers was not necessary. During the 1976-77 winter the samplers were placed on a stage-activated system. A magnetic switch attached to a float tape in the stilling well activated a relay switch, which in turn activated the samplers. The incremental rise in stage needed for activation could be changed manually. Once activated, the sampler operated through the entire cycle of 28 bottles regardless of the water level in the stilling well. A constant sampling frequency of 0.5 hours with two samples per bottle was used in this setup. This system greatly increased sample precision, and allowed for easier data reduction. A schematic diagram of the switching device is shown in Appendix A.

The DH 48 sediment sampler was used at both study sites during several runoff events. Samples were taken at varying time intervals on three equally spaced vertical stream segments using the equal transit rate method (Guy and Norman, 1970). These measurements were designed to indicate variations in suspended sediment concentration (SSC) across the channel and short-term temporal variations (5 to 15 min) in the sampling cross section. DH 48 samples were also taken in conjunction with the ISCO samples to determine the representativeness of the pumping sampler system for sampling at these sites.

Streamflow measurements for both watersheds were made at permanent stream gaging stations. Concrete channel control structures had previously been installed at both sites: a rectangular flume in Oak Creek and a broad crested V-notch weir in Flynn Creek.

Velocity measurements were determined directly by current metering. At Flynn Creek, the stage-discharge relationships used in this study were those developed by the USDI Geological Survey at the same gaging station during the Alsea Watershed Study. Spot checks made on this relationship indicated that the rating curve had not changed significantly. The rating curve for Oak Creek was determined as part of a concurrent study (Heinecke, 1976). A more detailed discussion of the standard stream gaging procedures used at these sites can be found in Carter and Davidian (1968).

Both indirect and direct measures of suspended sediment concentration were used in this study. An indirect measure of sediment concentration (i.e. turbidity) was obtained using a Hach Model 2100A nephelometer. All sediment samples were analyzed for turbidity in the laboratory prior to the gravimetric analysis for SSC. The standard procedures recommended in the Hach Laboratory Instrumentation Manual were followed (Hach Chemical Company, 1973). All readings were taken on the 0-100 ntu (nephelometric turbidity units) scale using a 20 ml sample. Samples were thoroughly agitated before each reading. For samples with a turbidity of greater than 40 ntu, serial dilutions of 0.5, 0.1, and 0.05 were used to bring the reading down into the 0 to 40 ntu range. An appropriate dilution factor was then applied to this reading to obtain a turbidity value for the undiluted sample. This approach is required to reduce significant backscattering errors that occur at concentrations greater than 40 ntu (APHA, 1975).

The ISCO and DH 48 water samples were analyzed for SSC directly by using standard gravimetric-filtration procedures for filterable residues (APHA, 1975). Watman (FGC) 7 cm diameter filters were to facilitate rapid filtration of the samples. Multiple samples were run on a manifold filtration apparatus. A sample volume of 150 ml was normally used.

The filtrant was weighed in aluminum drying pans. The tare weights for each pan and the filter were subtracted from the gross weight to obtain a net weight for suspended solids. An average tare weight for the filter paper was calculated from random samples of filters taken from each box of filters.

Data Analysis Techniques

Cross-sectional channel profiles were measured during two consecutive summers on both watersheds. These profiles provide an index of stream channel disturbance (scour or deposition of sediment) on an annual basis.

The mass of fine sediment per unit area of stream channel was determined from samples of bed material. It should be emphasized that these values represent an annual estimate of channel scour, deposition, and fine sediment storage. They do not account for short term variations in these parameters. The sediment storage values, combined with the estimated channel scour and width information from the profile stations, provided an approximation of the total mass of fine sediment (kg) available for transport within both streams.

Stream discharge (Q) was chosen as the principal independent variable in the analysis of temporal SSC variability. It was believed to be the parameter most highly correlated to SSC which could be measured with relative ease. Other independent variables were generated from the discharge values, including the cumulative discharge (ΣQ), defined as the cumulative sum of discharge values measured at the time a sediment sample was obtained and the rate change in discharge (dQ/dt). Values of stream stage were taken from the analog water-level chart at half-hour intervals. Discharge values were then generated within the computer using stage-discharge rating equations developed for each measurement station.

The dependent variables used in the analysis were suspended sediment concentration (SSC), measured in milligrams of sediment per milliliter of water ($mg \cdot l^{-1}$), cumulative suspended sediment yield (ΣSSY) measured in kilograms of sediment (kg), and turbidity (T) measured in nephelometric turbidity units (ntu). Both turbidity and sediment concentration have been widely used for expressing the amount of particulate matter in suspension. SSC is a direct measurement of the mass of particulates in suspension while T is a measurement of the optical properties of these particulates in suspension. Although SSC and T are not the same, they are often positively correlated. Both simple and multiple-variable linear regressions equations were developed in this analysis. Forward selection and backstep procedures were used to develop the multiple regression equations (Draper and Smith, 1966; Guthrie, Avery and Avery, 1974).

The significance of individual independent variables was determined from the Student's t distribution. The significance of the overall regression equation was determined from the F distribution of the following ratio: mean sum of squares regression vs. mean sum of squares residual (Draper and Smith, 1966). All t and F tests were carried out at the 95% confidence level (95% CL).

RESULTS AND DISCUSSION

Laboratory Analysis of Suspended Sediment Samples

Both a direct and an indirect means of measuring sediment concentrations were utilized. The standard filtration-weighing procedures, the direct means of determining SSC, was evaluated using split samples. No significant difference between the first or second subsamples was found, based on a two-sample comparison. This indicates that through agitation prior to removing subsamples resulted in a fairly uniform distribution of the particles in suspension. The overall precision of this measurement procedure was evaluated by a confidence interval estimate of the two subsample means (Petersen, 1973). The estimate of the true mean at the 95% confidence level was between -3.9 and 7.6 mg/l of the sample means. This error can be attributed to variations in estimated filter tare weights, and in the weighing procedures. An analysis of filter paper tare weights shows a mean coefficient of variation of 5% (Petersen, 1973). Small errors associated with absorption of atmospheric moisture by the filtrant during weighing could not be evaluated quantitatively. As mentioned previously errors related to settling of the suspension did not appear to be significant. The overall effects of these measurement errors would obviously have the greatest affect on samples with low concentration (20 mg/l^{-1} or less), due to the poor resolution of the procedure at these levels. Turbidity, an indirect measure of suspended sediment concentration, was also evaluated. Figure 10 is a plot of SSC vs. T fitted using a least squares regression procedure.

In this case, the turbidity samples were diluted so that they fell within the 35-40 ntu range and a dilution factor was applied to obtain a turbidity estimate. This procedure is required to reduce the effect of backscattering at the higher sediment concentrations. Figure 11 shows that the SSC-T relationship is a curvilinear function when no dilutions are made.

Spatial Variability of Suspended Sediment Concentrations at Oak Creek

Sampling the spatial variation in suspended sediment concentration was a necessary prerequisite in order to define temporal variability, one of the primary objectives of this study. Analysis of horizontal and vertical distributions of sediment concentration were utilized to determine the spatial variability.

It was suspected that turbulent flow patterns through the gaging section tend to reduce horizontal gradations in sediment concentrations; the influences of turbulent eddy currents tend to randomly disperse the suspended load across a channel. The relatively small particles (silt and clay size ranges) which make up the majority of

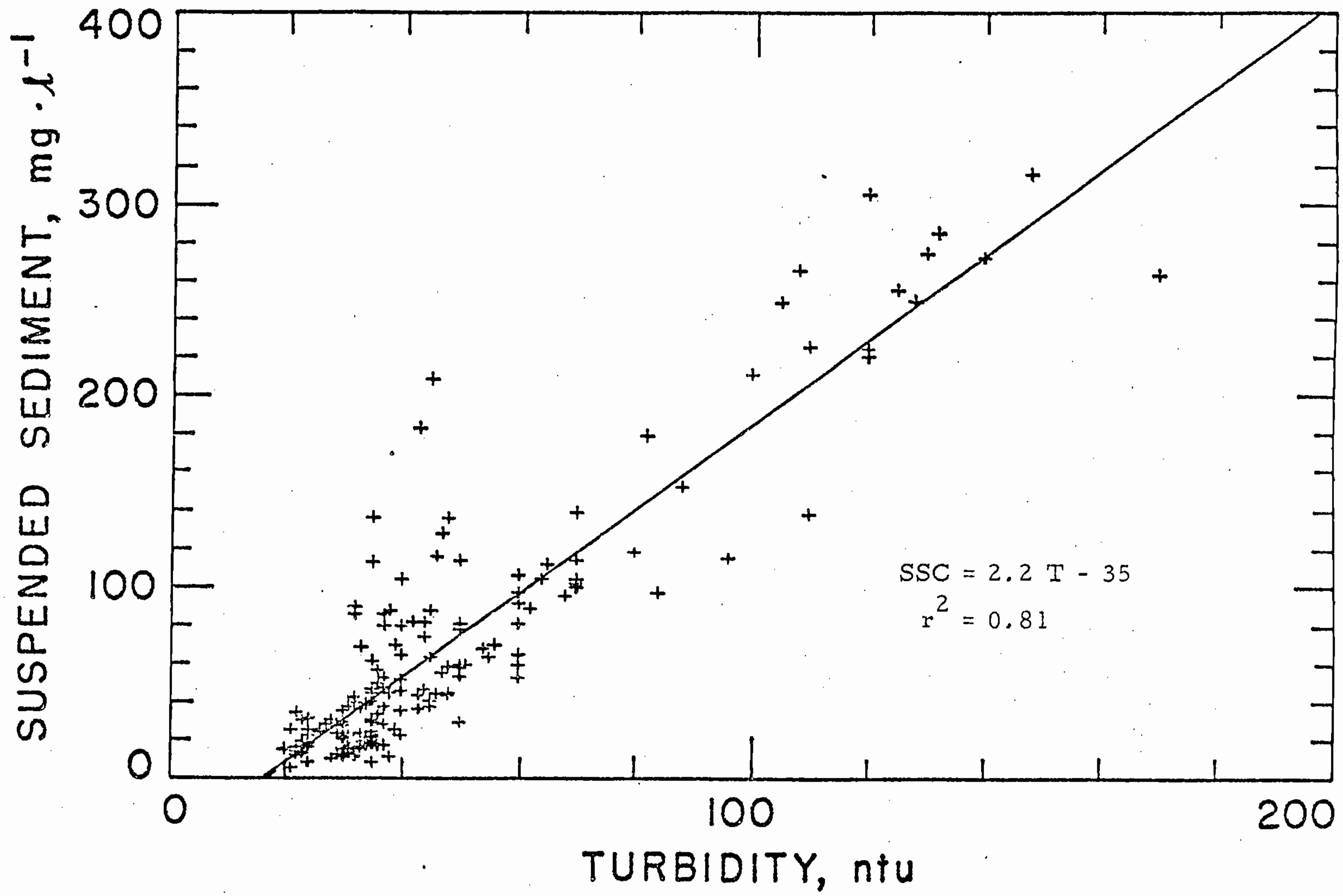

Figure 10. Relationship between suspended sediment concentration (SSC) and turbidity (T) for Oak Creek, 1975-76 winter.

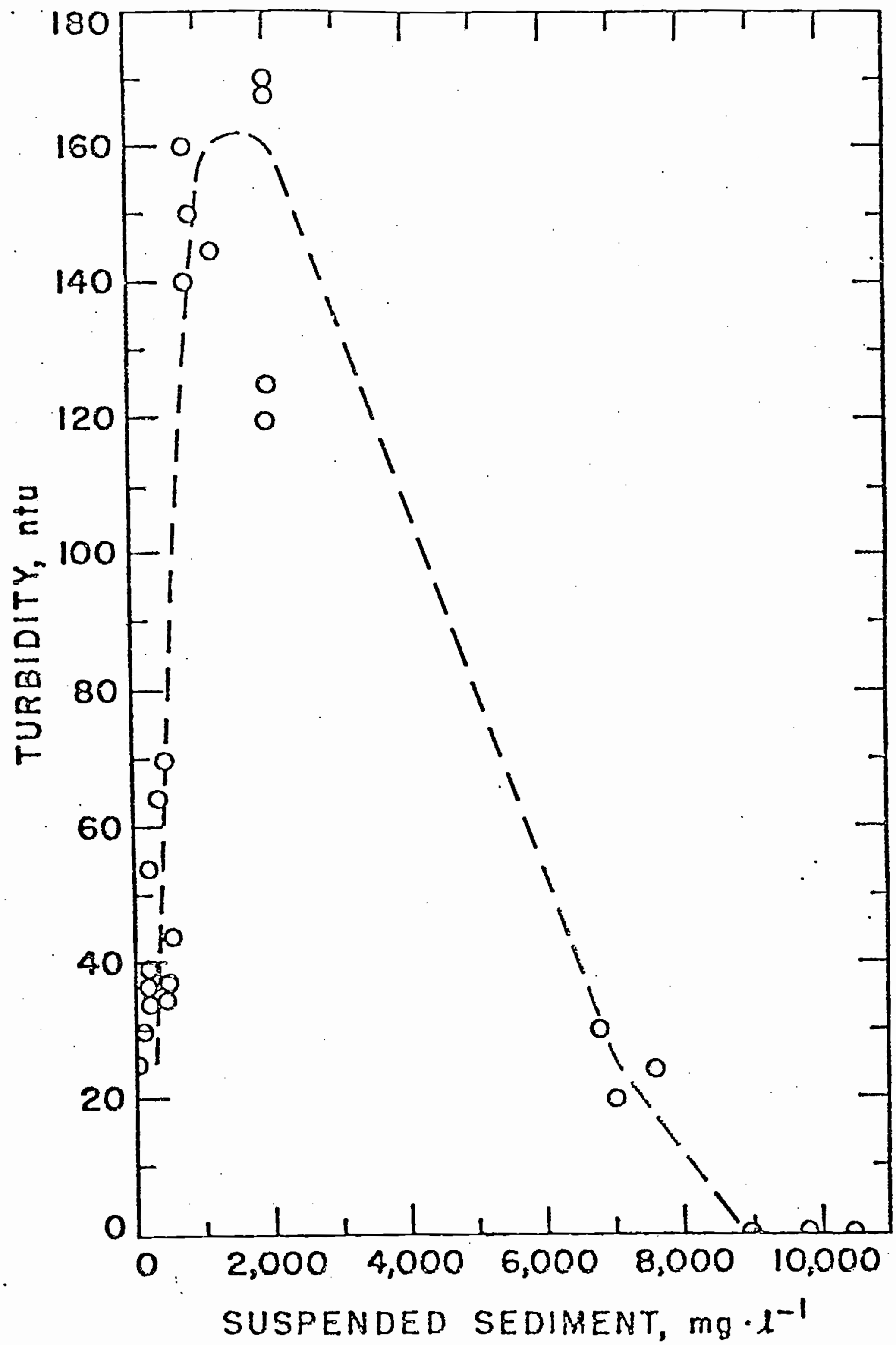

Figure 11. Relationship between turbidity and suspended sediment concentration (samples obtained from Oak Creek bed material analysis).

the suspended load should therefore not be greatly affected by horizontal velocity gradients. A comparison of mean suspended sediment concentration for samples taken at the center and the sides of the stream cross section showed no significant difference (95% CL) with 18 degrees of freedom (df). Variation about the group sample mean from the true mean of ± 7% was derived for the data using a nomograph described by Guy and Norman (1970).

The results of the ISCO and DH 48 comparison indicate that vertical stratification of the suspended load is taking place in the stream. A two-sample comparison between simultaneous ISCO and DH 48 samples showed a significant difference between the two sampling techniques. An estimate of the confidence interval of these data showed the concentration of ISCO samples varied 8 to 45 mg/l^{-1} greater than the DH 48 concentrations. The DH 48 samples are an integrated value of the vertical sediment concentration gradient. The ISCO sampling intake was located within a few centimeters of the channel bed under most flow conditions. A similar comparison between the two instruments showed that there was no significant difference between the two instruments when sediment concentrations were under 54 mg/l^{-1} (14 df). Sample comparisons above are based on the techniques illustrated by Petersen (1973).

Temporal Variability in the Suspended Sediment Regimes of Oak and Flynn Creeks

The influence of concentration variability over very short time spans was investigated. Two groups of samples were taken at 5 minute intervals over a period of 20 to 30 minutes to determine if short-term pulses of sediment were affecting the results. The data showed no significant variations that are not attributable to the random sampling error of 7% (Guy and Norman, 1970).

The primary objective of this study was to characterize the temporal variability in the suspended sediment regimes of Oak and Flynn creeks. A detailed analysis was made from data collected on Oak Creek. Measurable sediment yields from Flynn Creek occurred primarily during one large storm within the study period. Only a limited number of sediment samples was obtained for this event. These were not sufficient for carrying out an in-depth analysis.

Sediment concentration measurements must be correlated to one or more watershed factors or parameters before any meaningful information can be obtained from them. Several empirical relationships involving a number of various hydrologic factors have been illustrated in the literature (Hansen, 1966; Flaxman, 1975; Hindall, 1976). In this study, sediment concentrations and yields were related to one of the most basic hydrologic parameters, stream discharge. This approach has been one of the most widely used means for sediment predictions. The sediment-discharge rating curve method is the standard procedure used by the USDI Geologic Survey in predictions of sediment discharge for river and stream networks (Porterfield, 1972). However, studies conducted on small watersheds in the Oregon Coast Range have shown that a simple SSC vs. Q relationship is unreliable in characterizing sediment yields for these types of streams (Williams, 1964; Brown and Krygier, 1971; Brown, 1972; Moring, 1975). Results of SSC vs. Q measurements compiled during the 1976 water year for Oak Creek seem to support this conclusion (Figure 12). The equation for the fitted regression line (Oak Creek storms 1-6 combined) is illustrated in Table 1. Although the regression is statistically significant it is nevertheless characterized by a large amount of scatter about the regression line. Porterfield (1972) points out that on many small drainages the sediment concentration peak often precedes the hydrograph peak. If this phenomenon is occurring on Oak Creek, dividing the data into rising limb and falling limb components should improve the results. In Figures 13 and 14 the SSC vs. Q data are divided into rising and falling limbs of the hydrograph, respectively. The rising and falling limb regression equations (Table 1) were tested using the extra sum of squares principle to determine if a significant difference exists between the two regression equations (Draper and Smith, 1966). Results of the analysis showed that the rising and falling regression

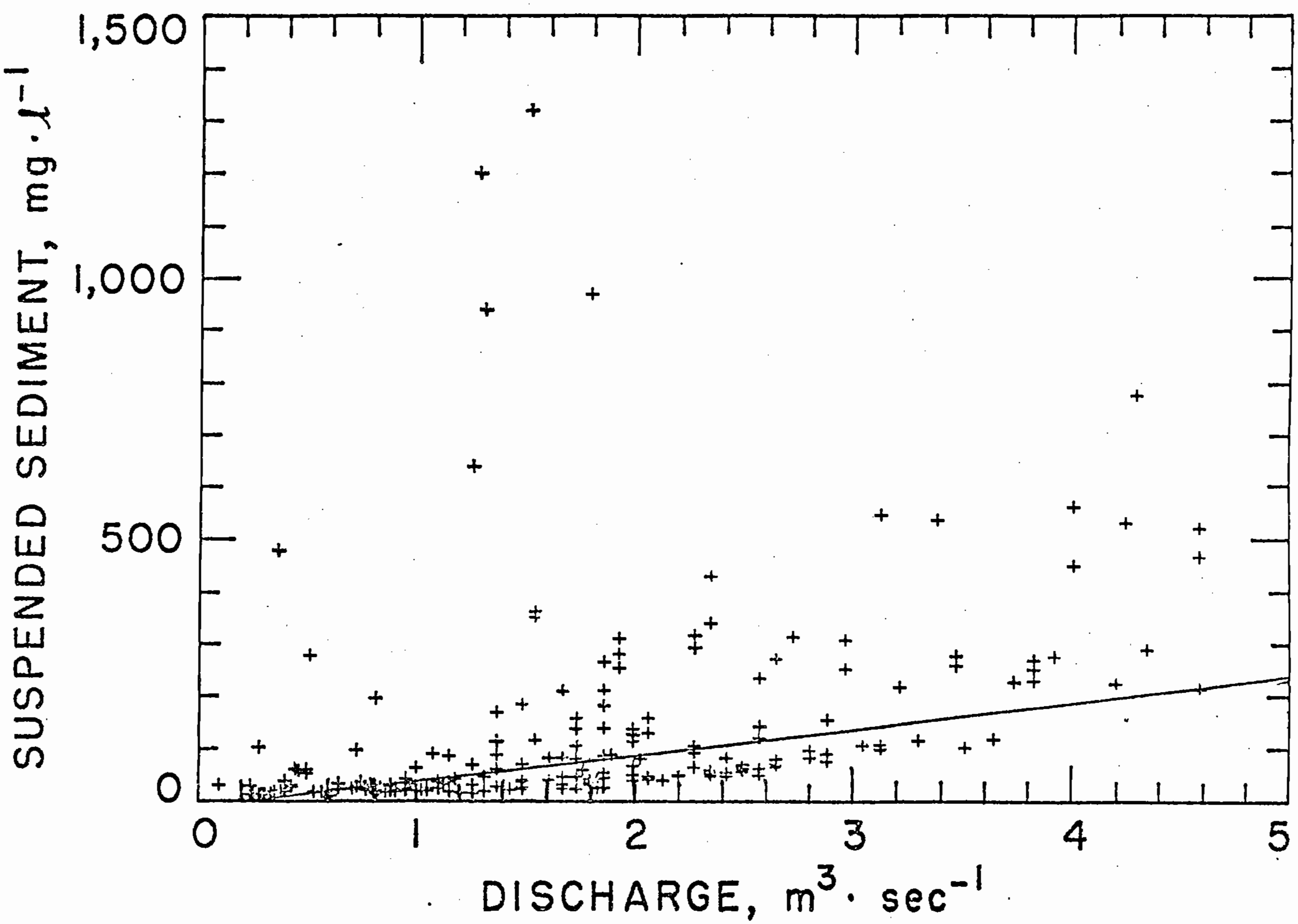

Figure 12. Relationship of suspended sediment concentration to discharge for Oak Creek, 1975-76 winter.

Table 1. Regression results of suspended sediment concentration and streamflow data for Oak Creek, 1975-76 winter.

Hydrographs	Number of observations	Regression equation 1/	r^2	Significant F 2/
Storms 1-6 rising	65	SSC = 50Q + 103	.63	*
Storms 1-6 falling	120	SSC = 70Q - 20	.20	*
Storms 1-6 combined	185	SSC = 50Q - 11	.49	*

1/ SSC = Suspended Sediment Concentration (mg/l^{-1})
Q = Discharge (m^3/sec^{-1})

2/ * indicates significant at 95% confidence level

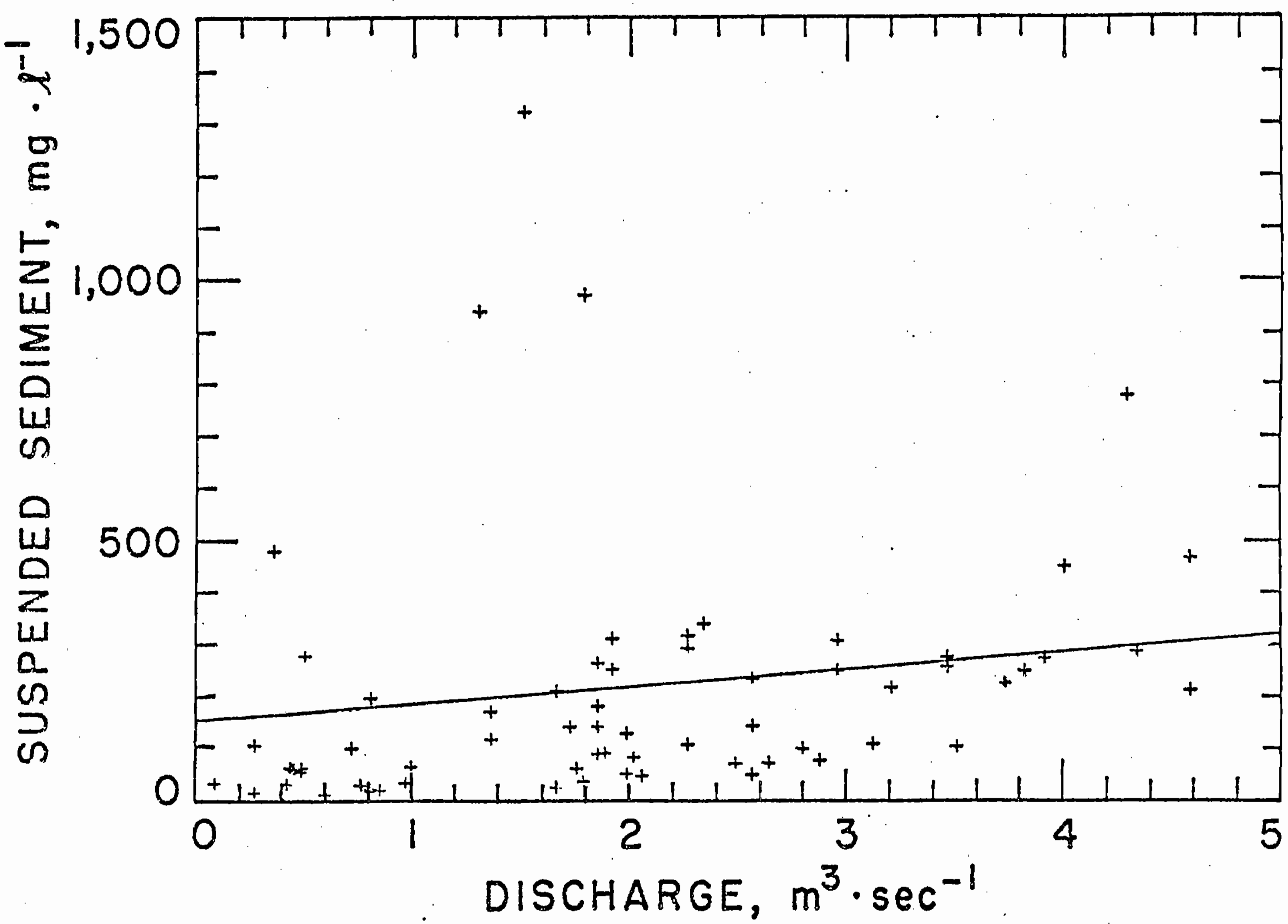

Figure 13. Rising limb suspended sediment concentration vs. discharge for Oak Creek, 1975-76 winter.

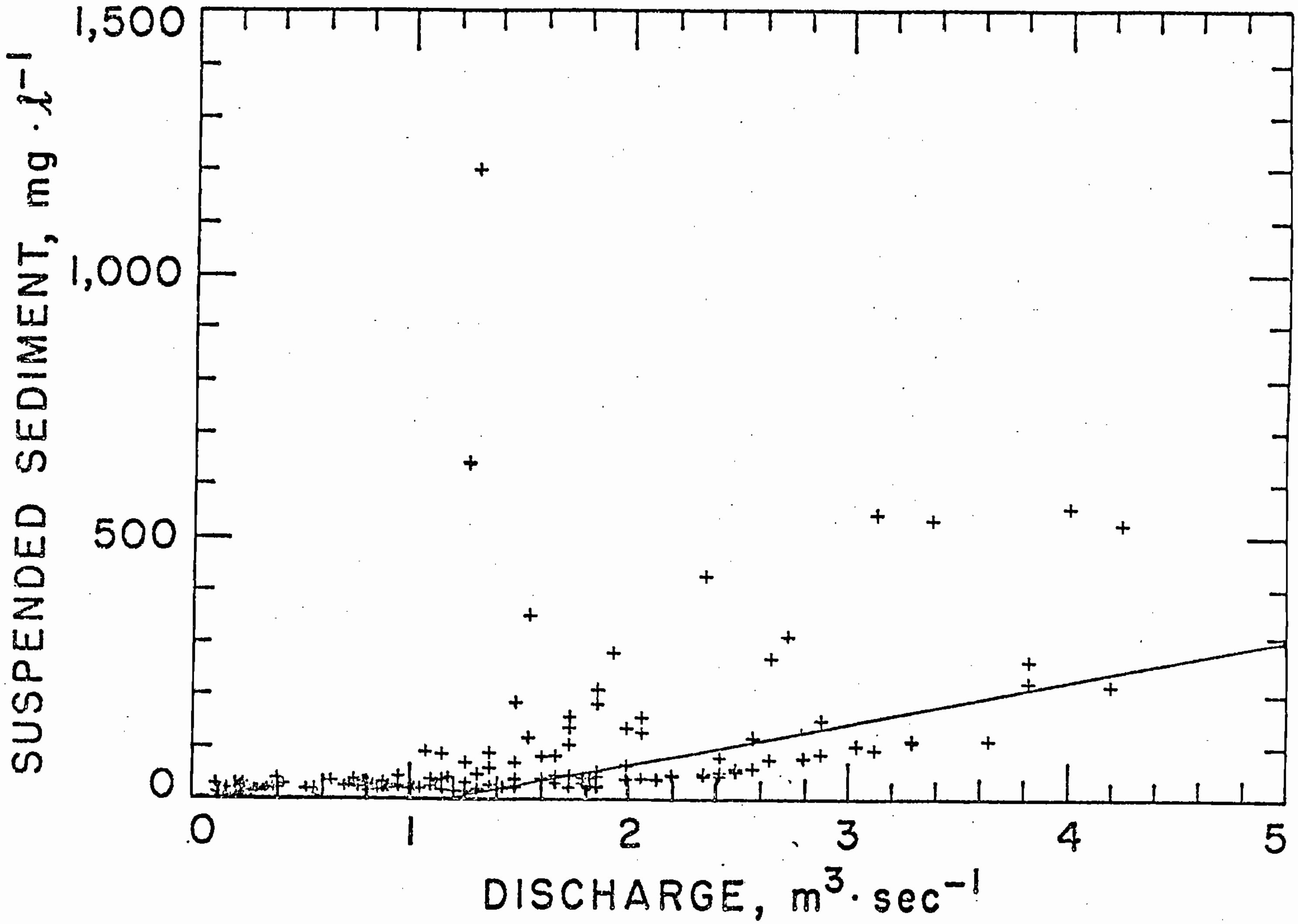

Figure 14. Falling limb suspended sediment concentration vs. discharge for Oak Creek, 1975-76 winter.

equations are significantly different. These results indicate that a simple sediment to discharge relationship for the entire runoff season is not adequate to describe the suspended sediment transport variability.

A detailed look at sediment yields for individual storms may provide a better indication of some of the sources of variation affecting the annual SSC to Q relationship (see Figure 15). For example, decreases in sediment yield are evident for storms of comparable peak discharges as the runoff season progresses (storms 1-6). In fact, the relative magnitude of the peak discharge seems to have little effect on the corresponding peak sediment concentrations following the second major storm 2 in December. Another interesting point is that sediment concentration peaks slightly precede the hydrograph peaks in most storms. This effect is particularly prominent in storm 1. These results are consistent with the idea that the transport of most loose soil and sediment particles will be initiated during the rising limb of the storm hydrograph.

Milhouse and Klingeman (1973) have concluded from previous studies on Oak Creek, that channel bed disturbances exert a considerable influence on the stream's suspended sediment regime. In their conceptual model of sediment transport, stable streambed gravels have the capability to filter out fine sediment particles, and store them for release at a later time.

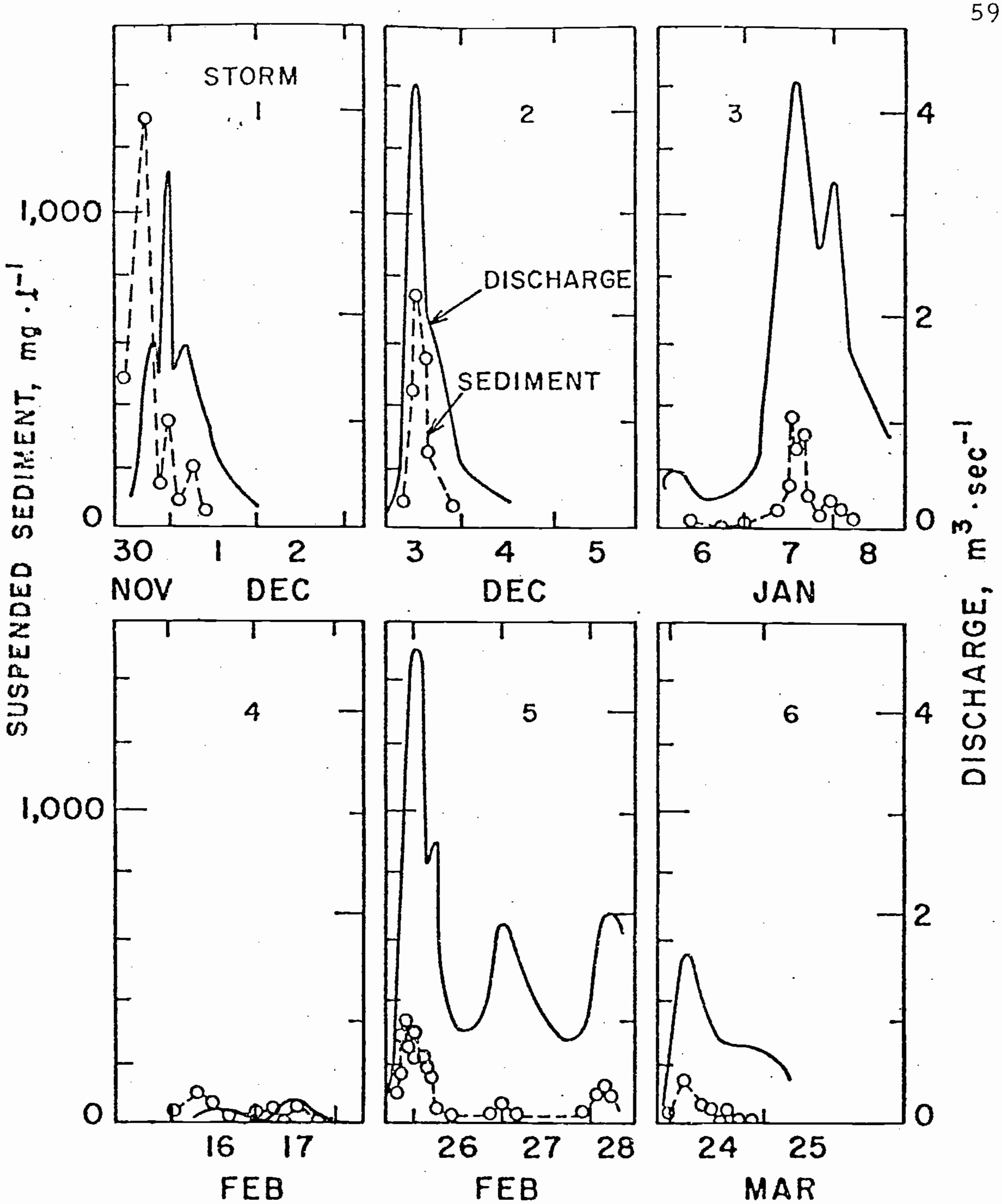

Figure 15. Individual storm hydrographs and suspended sediment concentrations for Oak Creek, 1975-1976 winter.

The release of fines from this storage reservoir is largely controlled by the armor layer. In general, the greatest disturbance of the armor layer occurs on the rising limb of the hydrograph (Milhous and Klingeman, 1973). This results in an initial pulse of high SSC on the rising limb of the hydrograph as the armor layer disintegrates. Once the armor layer has reestablished itself near the peak of the hydrograph, less fine material may be available for transport. Once the stream has armored, secondary hydrograph peaks may be associated with relatively lower suspended sediment concentrations. Again referring to Figure 15, the storms with multiple peaks (storms 1, 3, 4, 5) do have much smaller secondary suspended sediment peaks in proportion to their discharge than does the initial peak discharge. This lends support to the hypothesis that in-channel sediment sources have a major influence in this stream's sediment regime. Porterfield (1972, p. 28) relates a pertinent example of how two different streamflow regimes affected the sediment discharge characteristics on the Rio Grande River. In his example, equal volumes of water were released at the same rate on two separate occasions where different initial flow conditions existed. Under low initial flow conditions ". . . the released water eroded sediment from the bed and the banks of the stream and caused an initial sediment pulse." With high initial flow, Porterfield found ". . . the change in stage and velocity is less and there is little or no additional erosion from the bed and banks of the stream by the initial increase in flow." This example indicates how sediment peaks can be influenced by the effects of previous flow conditions and the removal of sediment stored in the channel.

A comparison of SSC to discharge variables for individual storms is shown in Table 2. Three discharge-related, independent variables, discharge (Q), cumulative discharge (ΣQ) and rate change of discharge (dQ/dt), were used in developing the multivariable regressions. The selection of "best fit" regression equations was based on the r^2 value (sum of squares due to regression divided by the sum of squares about the mean for a multiple variable linear regression), the number of significant variables, and the significance of the overall regression equation. It should be noted that for most storms the equations are quite different. Although statistically significant relationships were obtained for all storms, the predictive capability of these equations is low based on their low r^2 values. The least significant relationships are in storm numbers 1 and 4 where the ratio of SSC to Q is highest. The coefficients in equations 3 and 5 are remarkably similar (Table 2). In comparing the sediment graphs and hydrographs of these storms (Figure 15), the hydrographs are of similar form and magnitude, and they have very similar SSC responses.

Table 2. Individual storm regression results for Oak Creek, winter 1975-76.

Storm	Number of observations	Regression equation 1/	r^2	Significant F 2/	Significant t 2/ Q	Q	$\frac{dQ}{dt}$
Oak 1	26	$SSC = -198Q - 13\Sigma Q + 134 \frac{dQ}{dt} + 1010$	.55	*	-	-	-
Oak 2	23	$SSC = 138Q - 31$	.62	*	*	-	-
Oak 3	73	$SSC = 53Q - .71\Sigma Q + 46 \frac{dQ}{dt} + 19$	.61	*	*	*	*
Oak 4	18	$SSC = 67Q - 6\Sigma Q + 265 \frac{dQ}{dt} + 23$	.46	*	-	*	-
Oak 5	36	$SSC = 53Q - 1.4\Sigma Q + 46 \frac{dQ}{dt} + 52$	.75	*	*	*	*
Oak 6	18	$SSC = 177Q + 3.6\Sigma Q + 201$	.97	*	*	*	-

1/ SSC = Suspended Sediment Concentration (mg/l^{-1})
Q = Discharge ($m^3\ sec^{-1}$)
t = time, one-half hour intervals

2/ * indicates significant at 95% confidence level
\- indicates not significant at 95% confidence level

A comparison of storm hydrographs and sediment graphs in Figure 15 and the individual storm regression equations illustrated several important relationships which can be summarized as follows:

(1) Decreases in sediment yield are evident for storms of comparable peak discharge as the runoff season progresses.

(2) Sediment concentration peaks slightly precede hydrograph peaks in most storms.

(3) Secondary SSC peaks are much smaller in proportion to their Q peaks on all storms with multiple hydrograph peaks.

(4) The shape of the storm hydrographs seems to affect the SSC vs. Q relationships; hydrographs that change rapidly have less predictable sediment concentrations; those storms which produce slowly changing hydrographs have more predictable sediment concentrations.

(5) Hydrographs of similar shape have similar SSC to Q relationships.

When the sediment concentration data are further broken down into rising and falling stages, a hysteresis effect becomes evident, as shown in Figures 16 and 17. Hysteresis occurs when sediment concentrations at a given discharge are greater on the rising limb of the hydrograph than on the falling limb. Note that the similarity in the hydrographs for storms 3 and 5 (Figure 15) is also reflected by the hysteresis curves in Figure 16. The hysteresis effect for storm 2

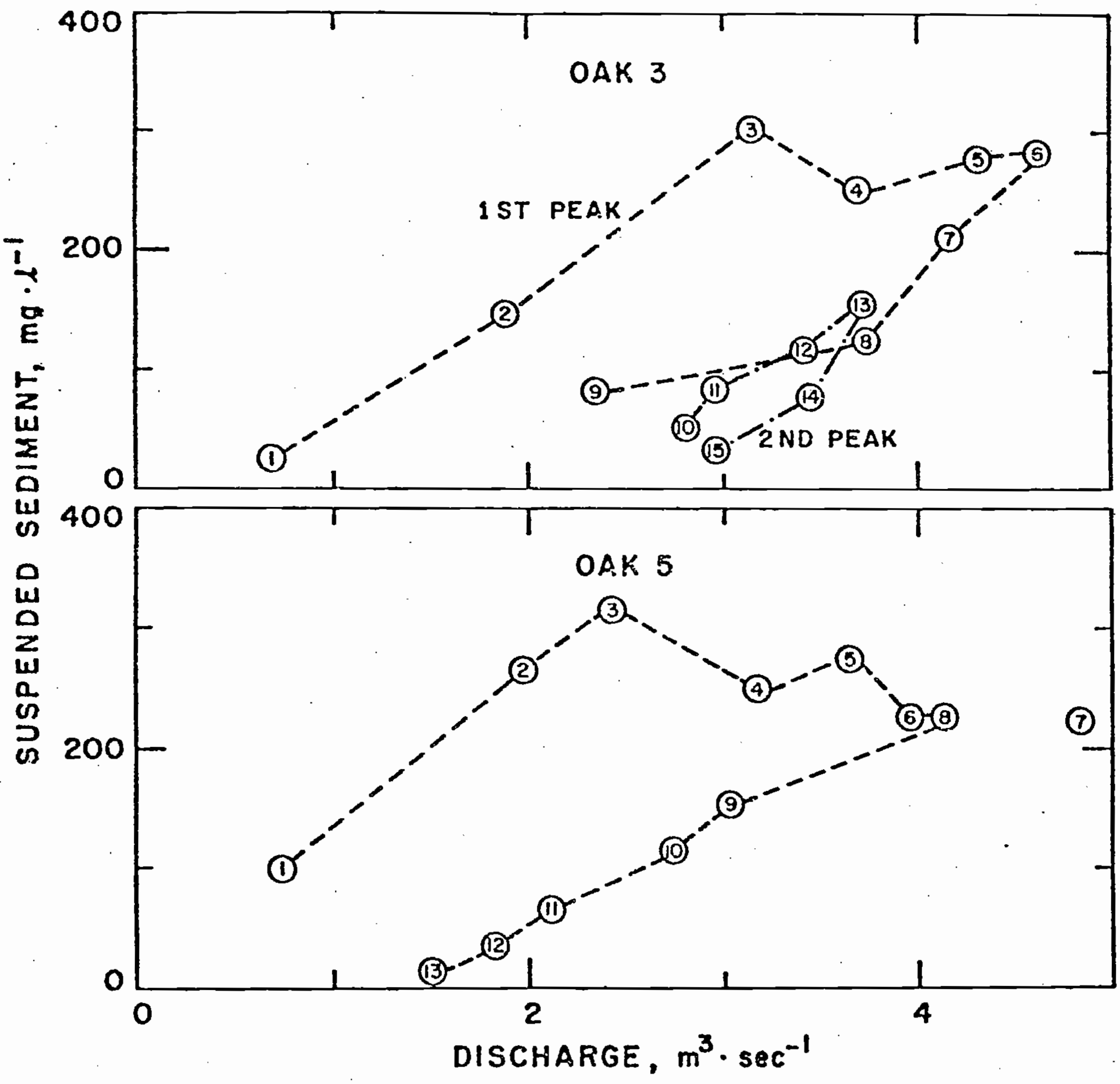

Figure 16. Hysteresis curve for storms 3 and 5 at Oak Creek, 1975-76 winter.

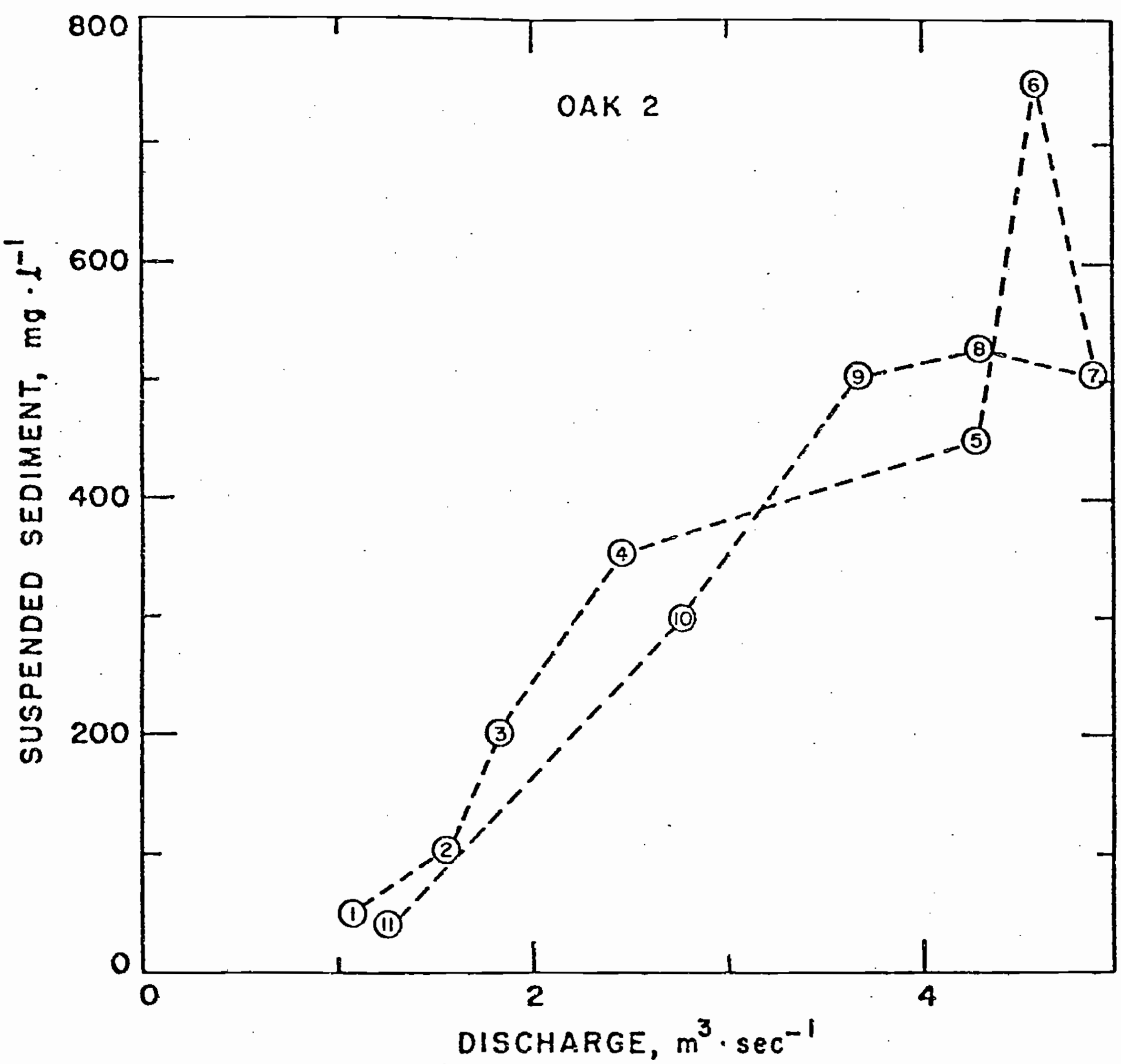

Figure 17. Hysteresis curve for storm 2 at Oak Creek, 1975-76 winter.

(Figure 17) is not as pronounced as in the other examples. Storm 2 has a very peaked hydrograph response, allowing a shorter period for the flushing of fine sediment. The more pronounced hysteresis loops for storms 3 and 5 may be associated with the relatively broad hydrograph response for these events. This allows for a longer period for the flushing of fine sediments from the channel and less available fine sediment on the falling hydrograph limb. These storms also occurred later in the year when there may be lower quantities of fine sediments in the bed available for transport.

Regression equations of selected storms for falling and rising sections, and the combined hydrograph are presented in Table 3. Dividing the hydrograph into two major components did improve the SSC to discharge relationships for some storms judging from the slightly higher r^2 values.

It is apparent that a general SSC vs. Q relationship cannot be readily derived for small gravel bottom streams such as Oak Creek. Even if multivariable empirical relationships could be derived for the suspended sediment regime of a stream, their applications would be limited. The difficulty and expense of obtaining enough data to define such a relationship would be a major problem. Also the relationships would probably not hold on other watersheds. The double mass technique is an alternative analytical tool that is useful for studying time trends in a relationship between two variables. The technique

Table 3. Within storm regression results of suspended sediment-concentration (SSC) vs. discharge (Q) for Oak Creek, 1975-76 winter.

Storm hydrograph	Stage	Number of observations[1]	Regression equation	r^2	Significant F[2]
Oak 2	rising	5	SSC = 177Q - 107	.88	*
	falling	15	SSC = 159Q - 104	.81	*
	combined	23	SSC = 138Q - 31	.61	*
Oak 3 1st peak	rising	4	SSC = 60Q - 108	.06	-
	falling	21	SSC = 39Q - 5.3	.84	*
Oak 3 2nd peak	rising	5	SSC = 81Q - 2.3	.81	*
	falling	22	SSC = 60Q - 82	.76	*
Oak 3 both peaks	combined	73	SSC = 43Q - 2.2	.34	*
Oak 5	rising	7	SSC = 32Q + 153	.29	-
	falling	11	SSC = 81Q - 94	.95	*
	combined	18	SSC = 2Q - 29	.76	*

1/ In some cases the combined regressions have a greater number of observations than the sum total of the rising and falling cases. This is due to the fact that observations of the hydrograph peaks and valleys have not been included.

2/ * indicates significant at 95% confidence level
- indicates not significant at 95% confidence level

tends to reduce the effect of variations due to individual measurements by deriving cumulative values for each variable over a given period. The cumulative value represents the incremental changes in each variable relative to the sum total of all previous measurements. Double mass analysis has been used successfully in several sedimentation studies. For example, Guy (1964) used the technique to study trends in sediment yield relating to changing land use patterns. Yorke and Davis (1971) used the technique in their study of the effects of urbanization on sediment transport in a small Maryland stream. Their results for cumulative sediment yield plotted against cumulative flow volume show a flat slope during the construction phase, indicating large amounts of sediment were released during the construction period.

Figure 18 is a double mass plot of cumulative suspended sediment yield (kg) vs. cumulative streamflow volume (m^3), for the major storm events during the 1975-76 winter. The resultant regression equation is as follows:

$$\Sigma SSY = 0.061\ \Sigma V + 16202 \ln \Sigma V - 145291$$

where:

ΣSSY = cumulative sediment yield (kg),

ΣV = cumulative streamflow volume (m^3).

Both independent variables ΣV and $\ln \Sigma V$ are significant at the 95% CL. Two important factors are indicated by this relationship. First,

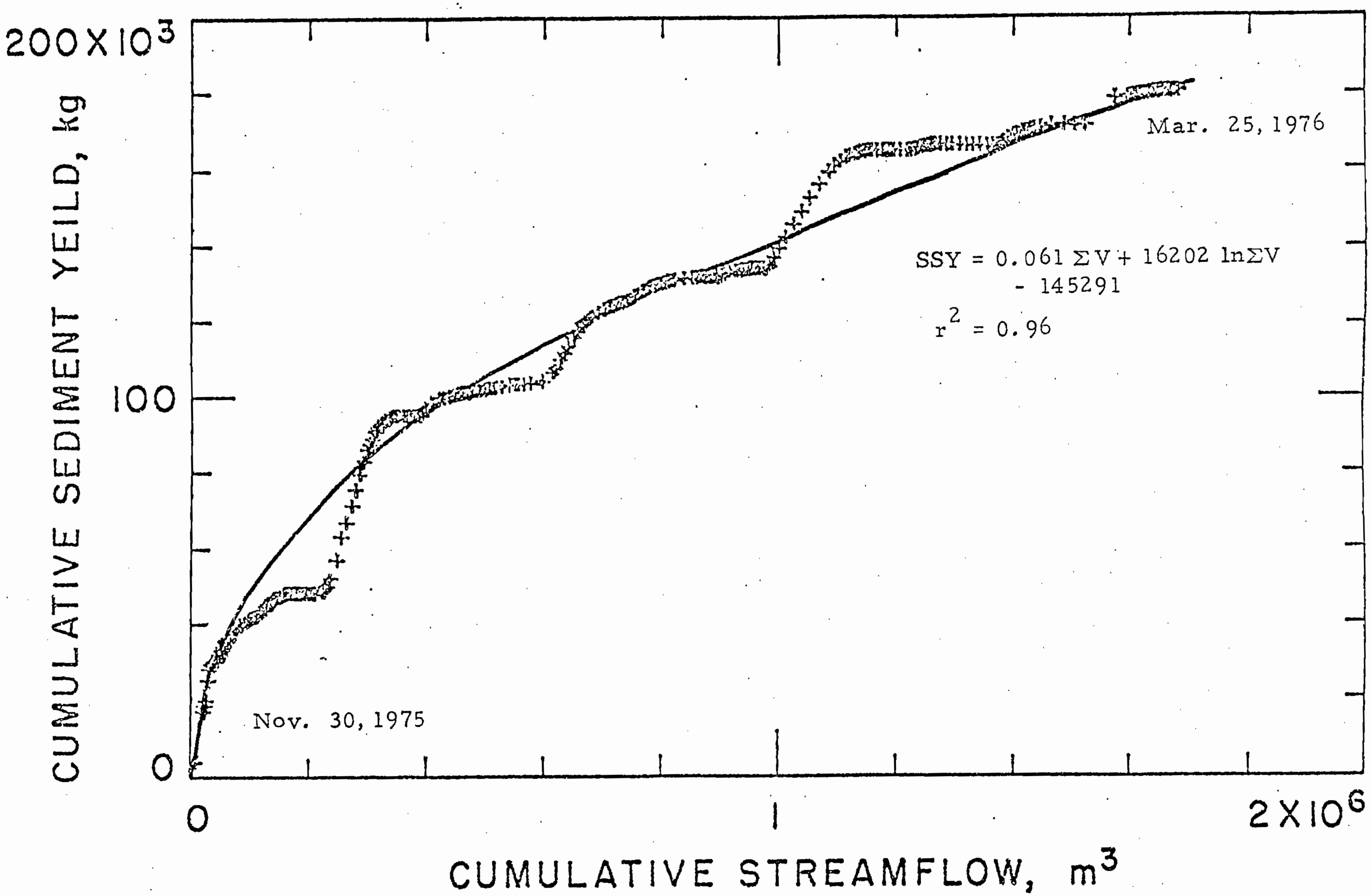

Figure 18. Double mass plot of cumulative suspended sediment yield (SSY) vs. cumulative streamflow volume (ΣV) for Oak Creek, 1975-76 winter.

the stairstep pattern of the data points is indicative of the hysteresis effect for individual storms noted earlier. A relatively steep slope occurs at the beginning of each storm when the sediment to discharge ratio is high. The slope gradually decreases as the suspended sediment to discharge ratio begins to decrease following the hydrograph peak. Secondly, the curvilinear trend of the regression line supports the idea that a "flushing" takes place over the winter runoff period. The steep slope for fall storms shows a relatively high sediment to streamflow ratio in comparison to the late winter or early spring storms.

The data presented for Oak Creek strongly suggest that the flushing of bed fines is an important factor in the sediment regime of this stream. Flushing occurs during storms and through the runoff season. Therefore, some means for the replenishment of bed fines must exist if this trend is to be sustained by the system. The conceptual model for suspended load transport presented by Milhous and Klingeman (1973) hypothesizes that a few large, stable armor particles provide sheltered areas which tend to trap fine sediments soon after general bed disturbance occurs at high flows. As the flow recedes and the bed armor is nearly reformed the gravel matrix begins to filter out large quantities of fines. As a result of lower quantities of fine sediment are available for transport once the armor layer begins to reform. The fine sediment stored in the bed gravels will be released upon the initiation of the next high flow event.

The quantity of fine sediments "flushed" from the stream is obviously influenced by the amount and timing of sediment inputs to the channel system. Several possible mechanisms exist for replenishment of fine sediments in the channel:

(1) Subtle erosional processes such as soil creep, bank caving, and dry ravel are contributing large amounts of sediment to the stream channel. Swanston and Swanson (1976) estimate soil creep rates in the western Cascades to be between a few milliliters to a few centimeters per year. However, an estimated annual supply of 64 metric tons/lineal km of stream/year of soil material can be delivered to a stream channel by this process. They indicate that this is a conservative estimate, assuming a creep rate of 10 mm yr^{-1} and 2 m high stream banks. This type of mass movement phenomenon is not uncommon on many Coast Range watersheds. No detailed geomorphic analysis of mass soil movement has been done on the Oak Creek watershed, but large proportions of the drainage basin do exhibit some degree of natural instability. Steep, undercut, raw soil banks are common channel characteristics. Slumps and earthflows adjacent to stream channels are evident in a few channel sections. These types of sediment inputs,

coupled with very low summer flows, could account for a large amount of sediment storage during this period. Subsequent high SSC values may result during initial fall storms.

(2) The effects of landslide activity which occurred during the 1964 and 1965 floods may still be influencing the sediment regime. During this period, large quantities of sediment were delivered to the channel from upslope areas. The hill slopes appear to be stabilized, but quantities of stored sediment in the channel may still be moved downstream during subsequent storm events.

(3) No detailed information about sediment storage behind large organic debris deposits is known for Oak Creek. However, large amounts of sediment can be trapped behind debris jams and later be released when the jams are washed away (Swanson, Lienkaemper and Sedell, 1976). Trees falling into the stream may also divert streamflow, initiating accelerated bank cutting. This effect can be particularly significant in streams such as Oak Creek where unconsolidated alluvium comprises significant amounts of channel banks and there are limited bedrock controls.

The scouring of stream banks and the undercutting and caving of banks during high flow periods undoubtedly makes significant contributions to the suspended sediment loads. Surface runoff from roads and trails in the watershed may also be significant sediment contributors. However, the relative importance of the many potential sediment sources is not known.

The extreme winter drought of 1977 resulted in a very limited amount of sediment transport information for that year. The few rainfall events which did occur were insufficient to initiate normal sediment movement. The significant suspended sediment transport was measured at the Flynn Creek station during this year. Two small storms did initiate some sediment transport in Oak Creek. The sediment graphs and hydrographs for these events are plotted in Figure 19. In comparing these results with the 1975-76 results shown in Figure 4, it is interesting to note the repetitious pattern of high initial sediment concentration peaks and lower secondary sediment peaks. This indicates that many of the characteristics observed earlier are not transitory phenomena. When storms 1 and 2 (Figure 19) of 1977 are compared to the 1976 late season storm 8 (Figure 15), significant differences in the sediment peaks are evident even though these storms are of similar magnitude. The recurrent pattern of relatively high early season sediment concentrations lends support to the theory that the fines reservoir is replenished to some extent during the spring, summer and fall dry period.

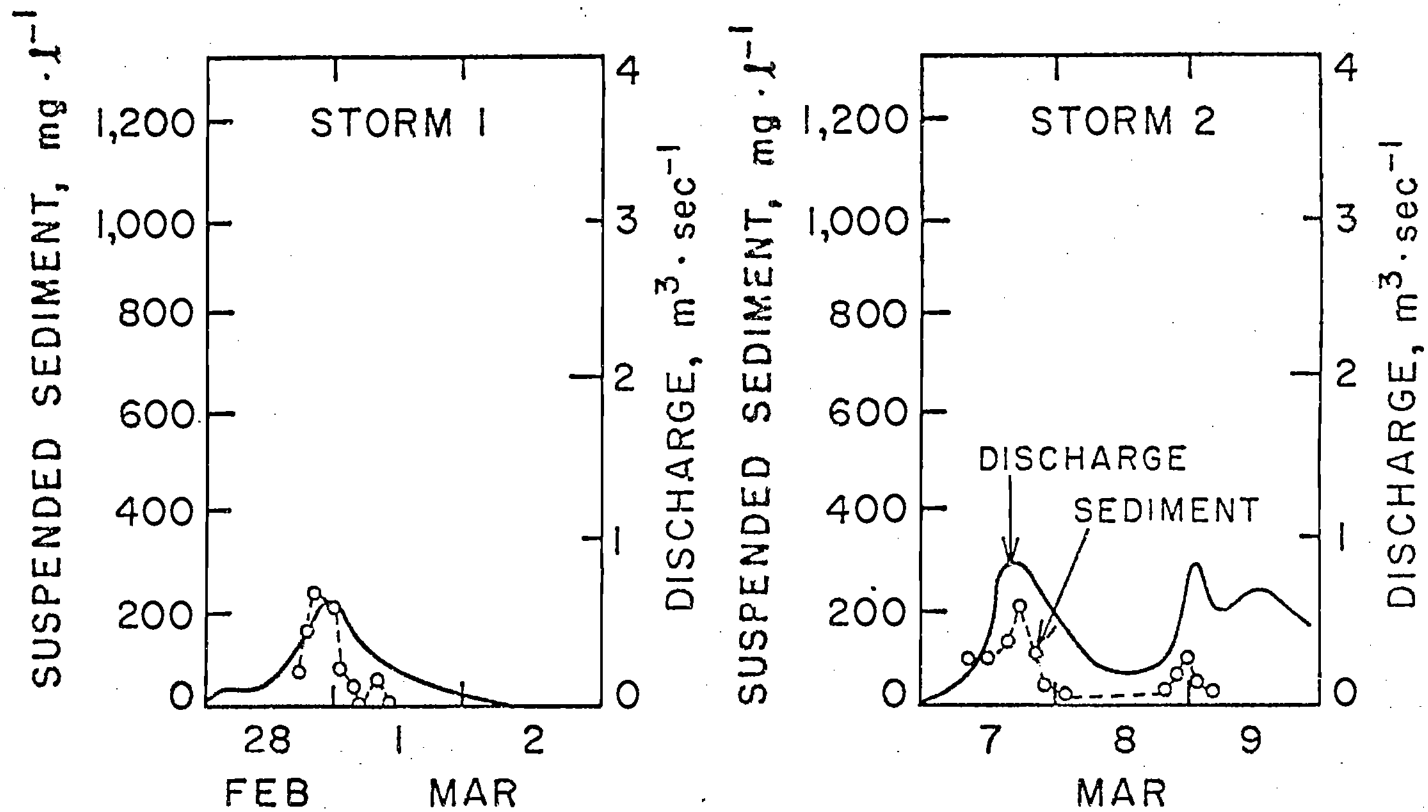

Figure 19. Storm hydrographs and sediment graphs for Oak Creek, 1976-77 winter.

Comparative Analysis of the Oak and Flynn Creeks Sediment Regimes

Three factors, climate, soils and geomorphology, determine erosional and sedimentation processes within a watershed. Oak and Flynn creeks have relatively similar climatic regimens and consequently similar vegetative cover. However, the geologic history of the two areas shows marked contrasts. The Flynn Creek basin has developed from uplifted coastal sediments whereas the Oak Creek basin is of volcanic origin (part of the Marys Peak intrusive formation). The basaltic soils of the Oak Creek watershed are fine textured with a high erosion potential (Table 4). In contrast, the soils of the Flynn Creek watershed, developed from sandstone parent material, have a much coarser texture and only moderate erosion potential (Table 4). Both watersheds have a history of mass soil movement on the steeper slopes. This activity has had a major influence on sedimentation rates during certain periods in the past, but was not believed to have been a major influence during this study.

A comparison of the watersheds' channel morphologies was made using techniques developed by Horton, Strahler, and Yang (Yang, 1971). Horton's stream laws and Strahler's ordering system were used to develop semilog plots of stream length, and stream slope for the Oak Creek and Flynn Creek watersheds (Figures 20 and 21). These morphometric parameters can be used to express the equilibrium

Table 4. General soils information for the study watersheds.

% Area	Soil Series	Texture	Runoff potential	Erosion hazard
		a. Oak Creek		
42	Dixonville	silty-clay-loam	very rapid	high
35	Price-Ritner	silty-clay-loam	rapid	high
20	Jory	silty-clay-loam	moderate	moderate
3	Wetzel	very cobbly-loam	very rapid	high
		b. Flynn Creek		
45	Bohannon	gravelly-loam	moderate-rapid	moderate-high
50	Slickrock	gravelly-loam	moderate	slight-moderate
5	Preacher	clay-loam	moderate	moderate

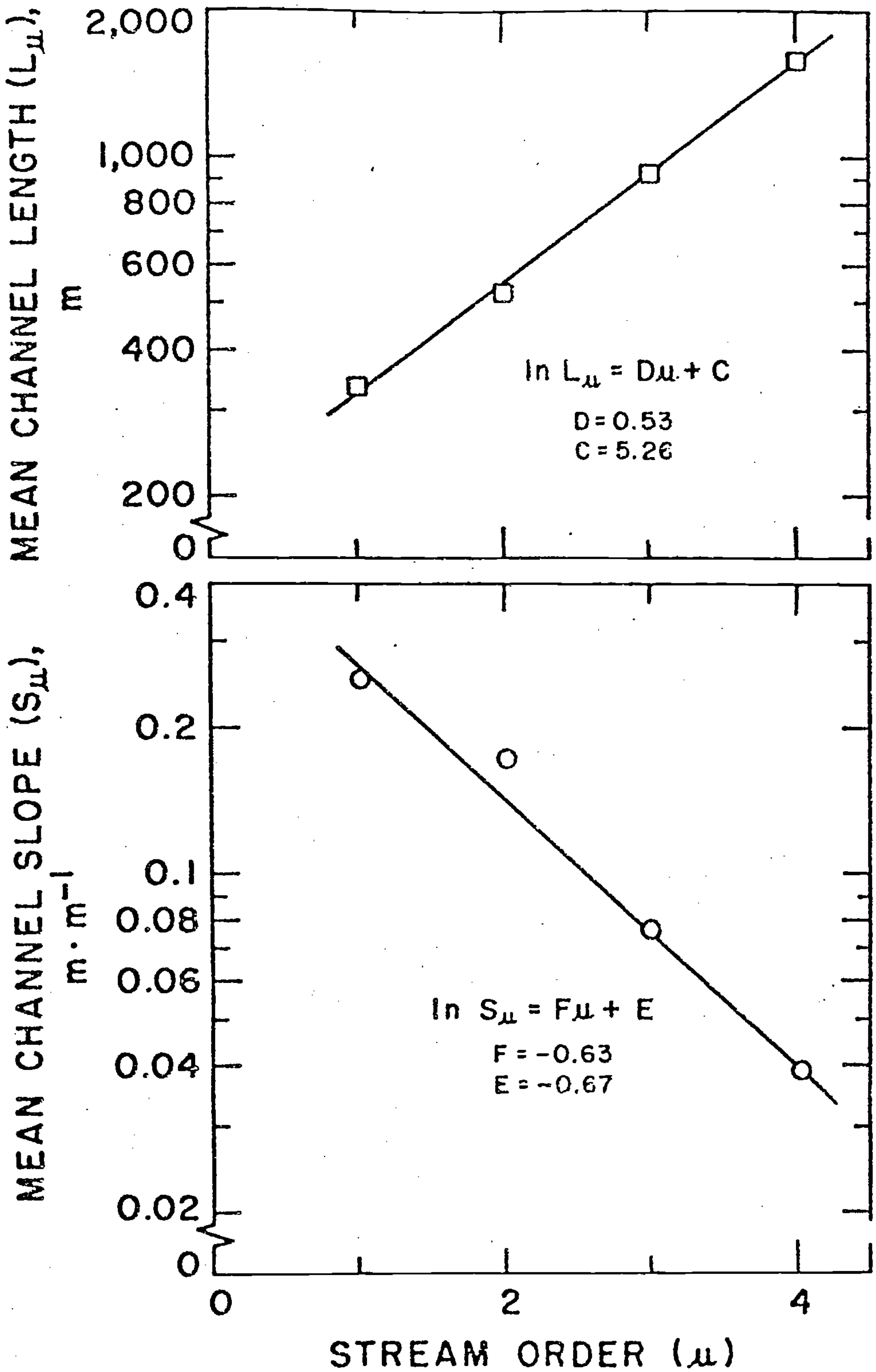

Figure 20. Horton-Strahler plots of mean stream channel length and slope for Oak Creek.

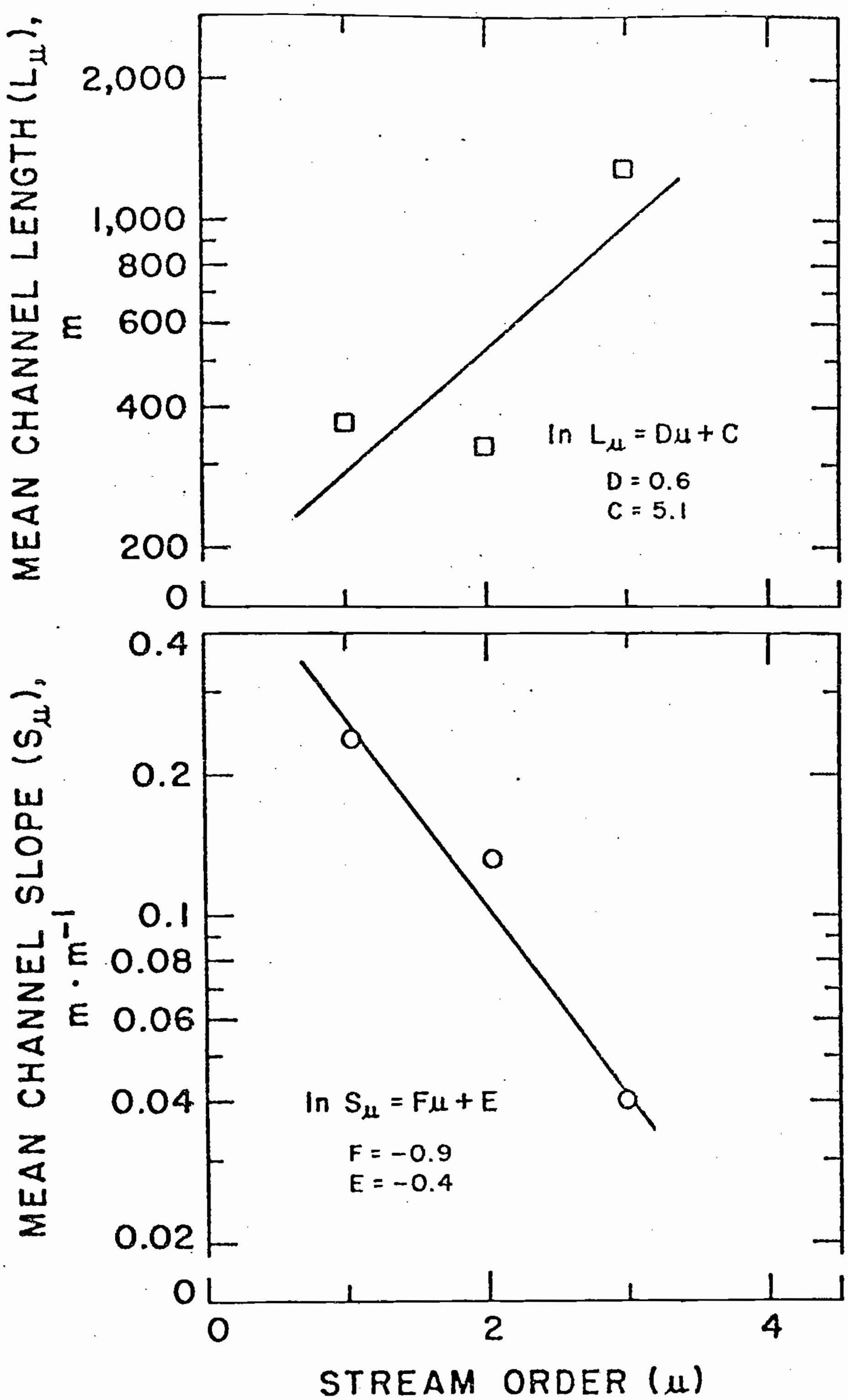

Figure 21. Horton-Strahler plots of mean stream channel length and slope for Flynn Creek.

status of a channel network and are based on stream morphology theories derived from Leopold's (1962) concepts of stream energy and entropy. The theories are "the law of average stream fall," and "the law of least rate of energy expenditure." The law of average stream fall is based on the premise that the most probable distribution of energy in a system is such that the entropy in the system is maximized when equal amounts of average fall exist in each stream order. The law of least rate of energy expenditure is derived from the concept that the production of entropy per unit mass of water should be minimized. When the conditions of these two laws are satisfied the stream is said to have reached a condition of dynamic equilibrium. This equilibrium state is subject to alteration by a variety of external constraints. These constraints include bedrock controls, changes in sediment load and changes in discharge. Figures 22 and 23 show longitudinal channel profiles of the two watersheds. The coefficients (C, D, E, F) used to develop the profiles were derived from the Horton-Strahler relationships in Figures 20 and 21. Profile I (Figures 22 and 23) represents an average channel profile and Profile II represents the theoretical equilibrium profile, where an equal average fall exists between each stream order (i.e., the fall ratio is equal to unity). The calculated fall ratios for both Flynn and Oak creeks are greater than 1.00, 1.35 and 1.11 respectively. Thus the watersheds should be in active states of degradation, attempting to

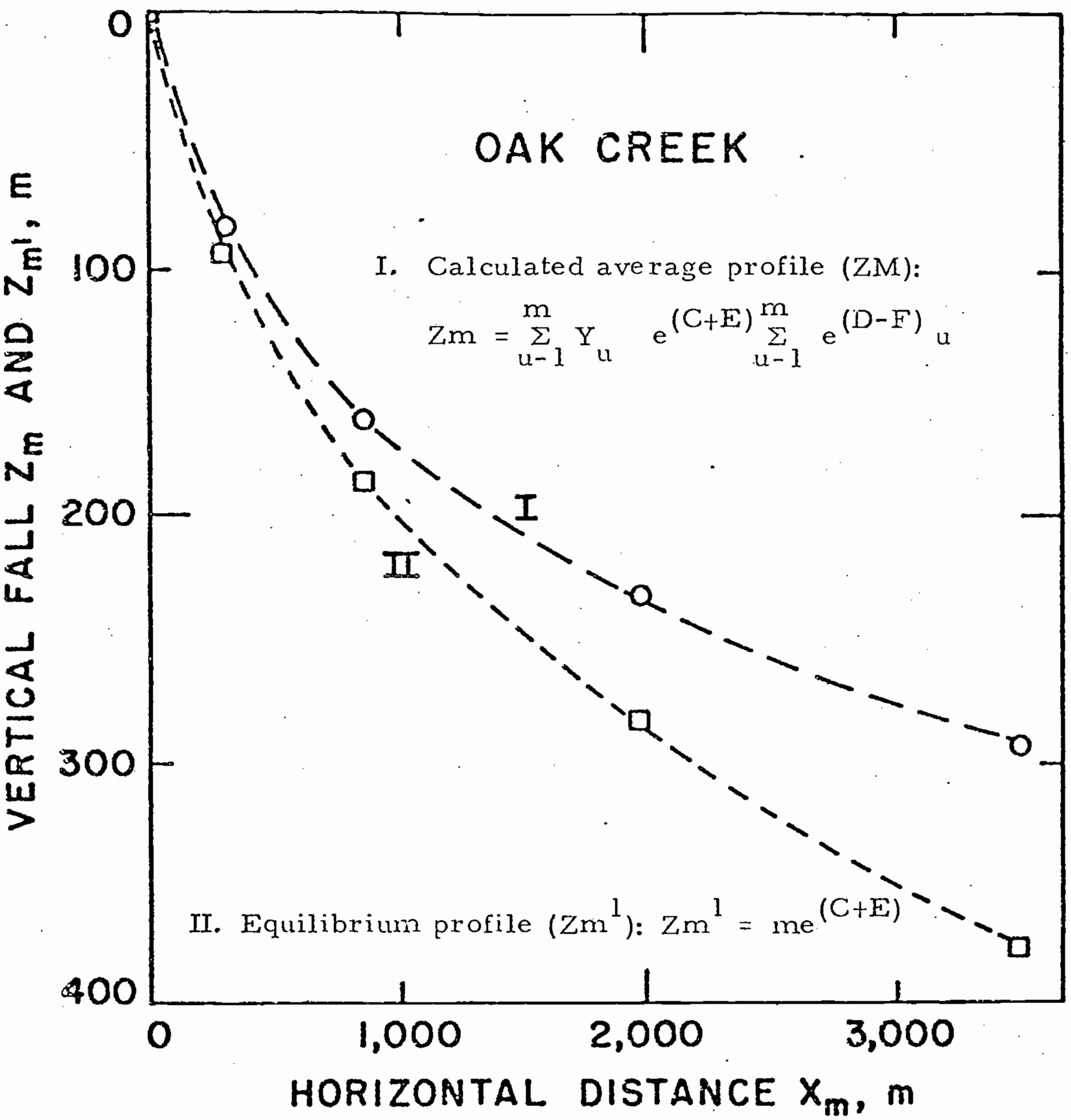

Figure 22. Longitudinal channel profile of Oak Creek.

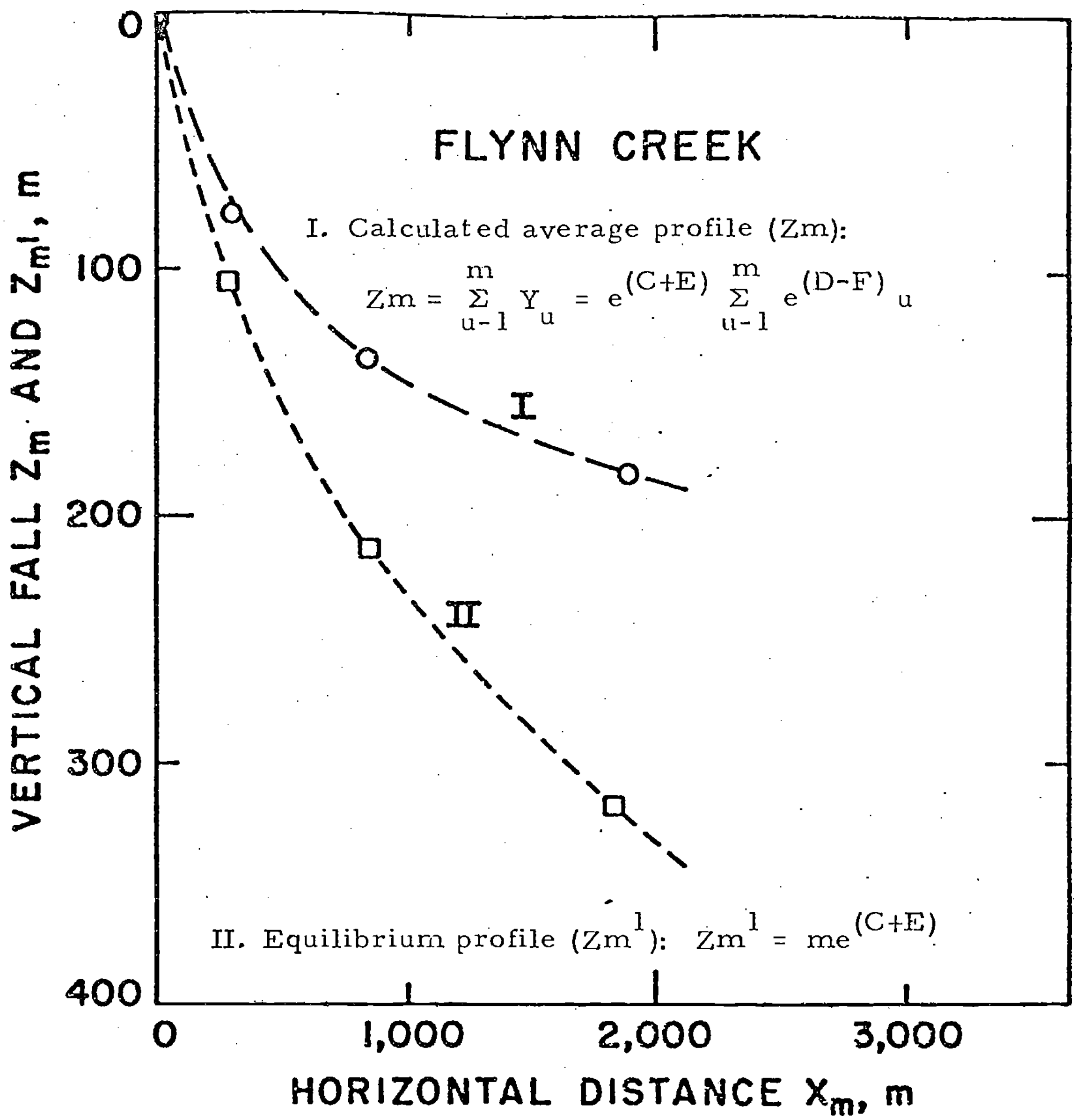

Figure 23. Longitudinal channel profile of Flynn Creek.

bring Profile I down to the level of Profile II. However, two constraints must be considered before accepting this conclusion. First, the watersheds parameters of length and slope must conform to the linear relationship defined by Horton's plots. Secondly, geologic anomalies such as waterfalls and bedrock chutes should not represent major barriers to channel development. Oak Creek meets these criteria fairly well. Flynn Creek, on the other hand, does not. A relatively poor fit of data points exists for the mean stream length relationship in Figure 21. From field observations it appears that geologic constraints have played a major role in the development of the Flynn Creek drainage network. Many of the second order stream channels are short, steep, bedrock chutes. The main third order channel appears to be a principal area of deposition for material scoured out of the lower order drainages. It thus has a relatively shallow gradient and does not seem to be undergoing the appreciable downcutting which would be expected from the channel morphology analysis.

A stream reach inventory and channel stability evaluation procedure (Pfankuch, 1976) was also used to determine the channel stability classes for Oak and Flynn creeks. Results indicated Oak Creek to be in the poor-to-fair category while Flynn Creek falls in the fair-to-good category.

Based on the available soils, geomorphology and channel stability information, some inferences relating to the sediment regimes of the two study watersheds can be made. The high soil erosion potential and unstable nature of the channels in the Oak Creek watershed would indicate relatively high sediment discharges from the stream. Flynn Creek, on the other hand, seems to have less erosive soils and more stable channel characteristics. Both watersheds have a past history of mass movements due to steep slopes on the upper reaches of the watersheds. As a result, large sediment discharges may occur on both watersheds during large, infrequent floods, when mass movement activity is most likely to take place.

Figures 24 and 25 show sediment graphs and hydrographs for the first large storm events in 1975, during which the relative magnitude of storm runoff is greater for Flynn Creek than for Oak Creek. However, the peak sediment concentrations are of greater magnitude for Oak Creek than for Flynn Creek. Figure 26 compares two storms of similar magnitude, where yields are greater for Oak Creek. For the several events which followed these storms, Oak Creek continued to exhibit significant suspended sediment loads, while Flynn Creek had little or no suspended material moving through the stream system. Sediment data collected on Flynn Creek during the Alsea Study showed a similar trend of high sediment yields for the large, infrequent storm events.

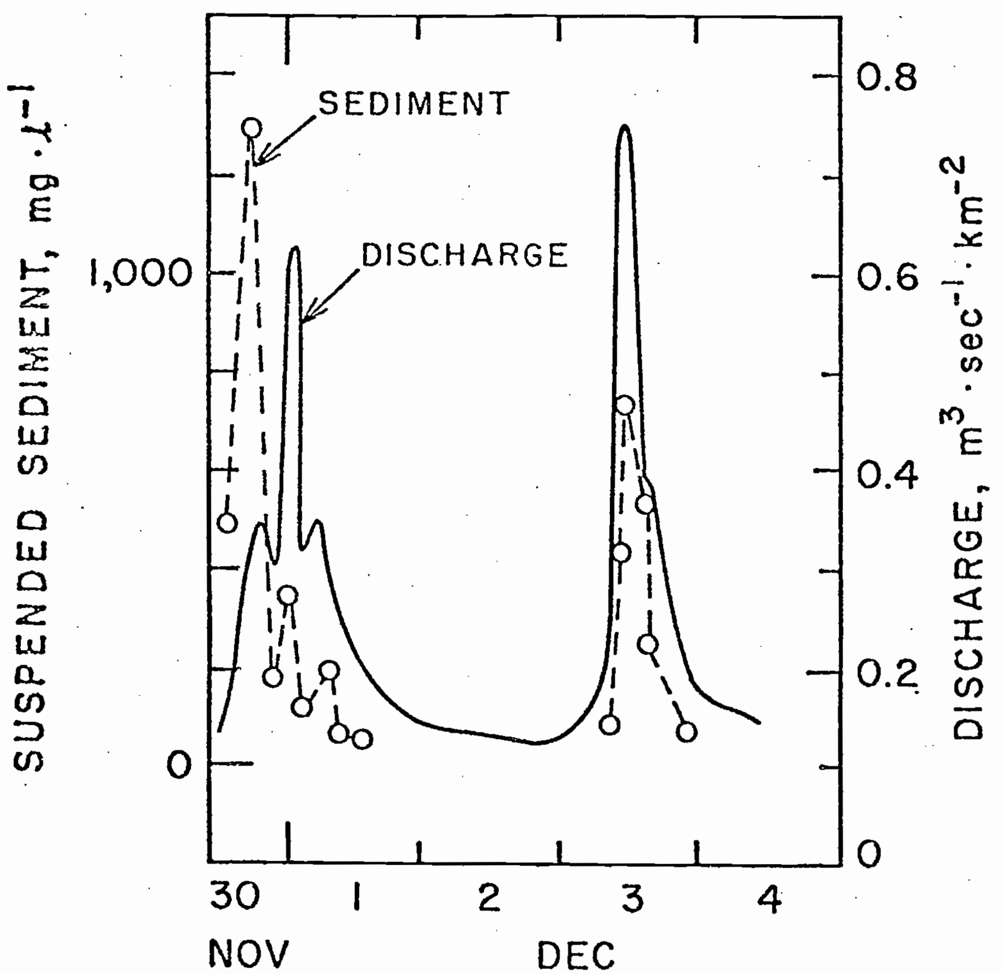

Figure 24. Suspended sediment concentrations and hydrograph for Oak Creek, 1975-76 winter.

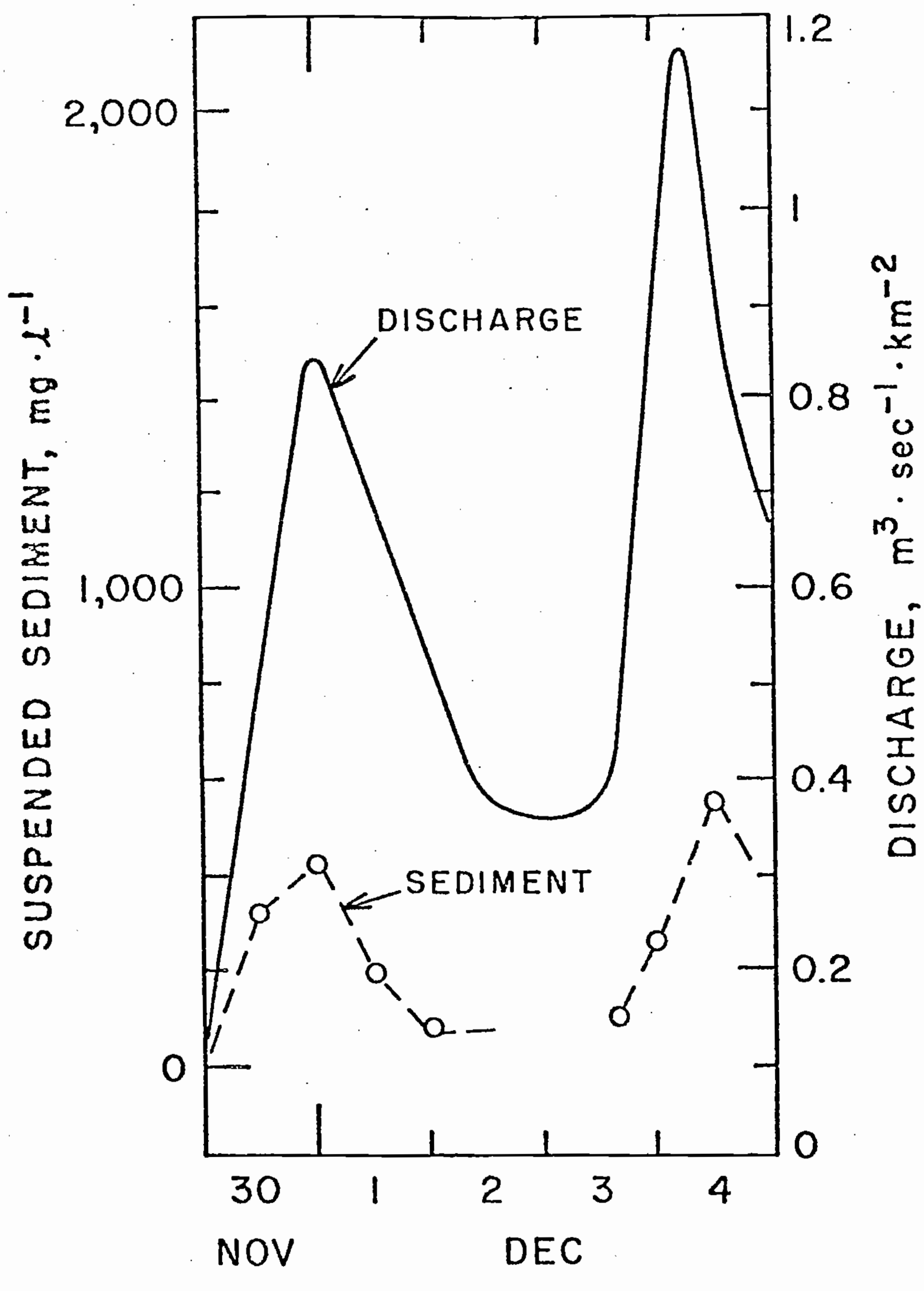

Figure 25. Suspended sediment concentrations and hydrograph for Flynn Creek, 1975-76 winter.

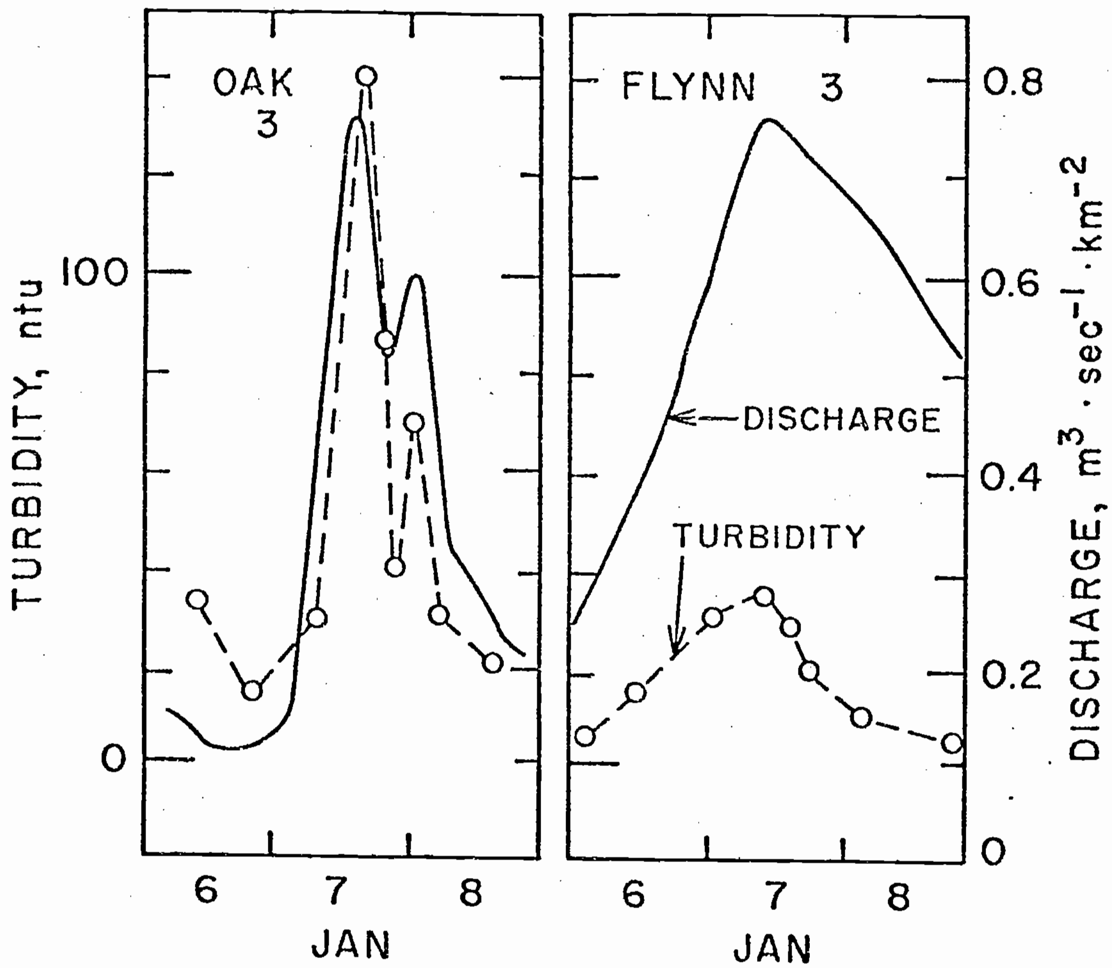

Figure 26. Hydrographs and turbidity graphs for Oak and Flynn Creek, 1975-76 winter.

In-Channel Sediment Source Areas

The streambed has been suggested as having an important influence on the sediment availability in gravel bottom streams. Thus the dynamics of scouring and filling of bed material is an essential factor in quantifying the effects of the bed on sediment transport. Channel profile measurements and scour chains were used at a limited number of stream locations on both watersheds in an attempt to characterize seasonal changes in the channel configurations. Figure 27 shows selected channel profile measurements for Oak Creek. Station 8 shows rather dramatically how a debris jam can affect channel stability in a stream section. In this case the jam, located 15 m above station 8 was partially washed out by high flows and deposited coarse sediments several feet downstream of station 9. In profile stations 9 and 12 there is evidence of alternate scour and deposition in the downstream direction. Heede (1972) also observed this phenomenon in gravel bottom streams in the Rocky Mountains. He attributes these distinct patterns of scour and deposition to adjustments of the stream to a new equilibrium profile. The cross-sectional profiles for Flynn Creek (Figure 28) illustrate less drastic seasonal changes in channel profiles in comparison to the Oak Creek profiles. This particular section appears to be relatively stable, with only a small amount of scouring and deposition.

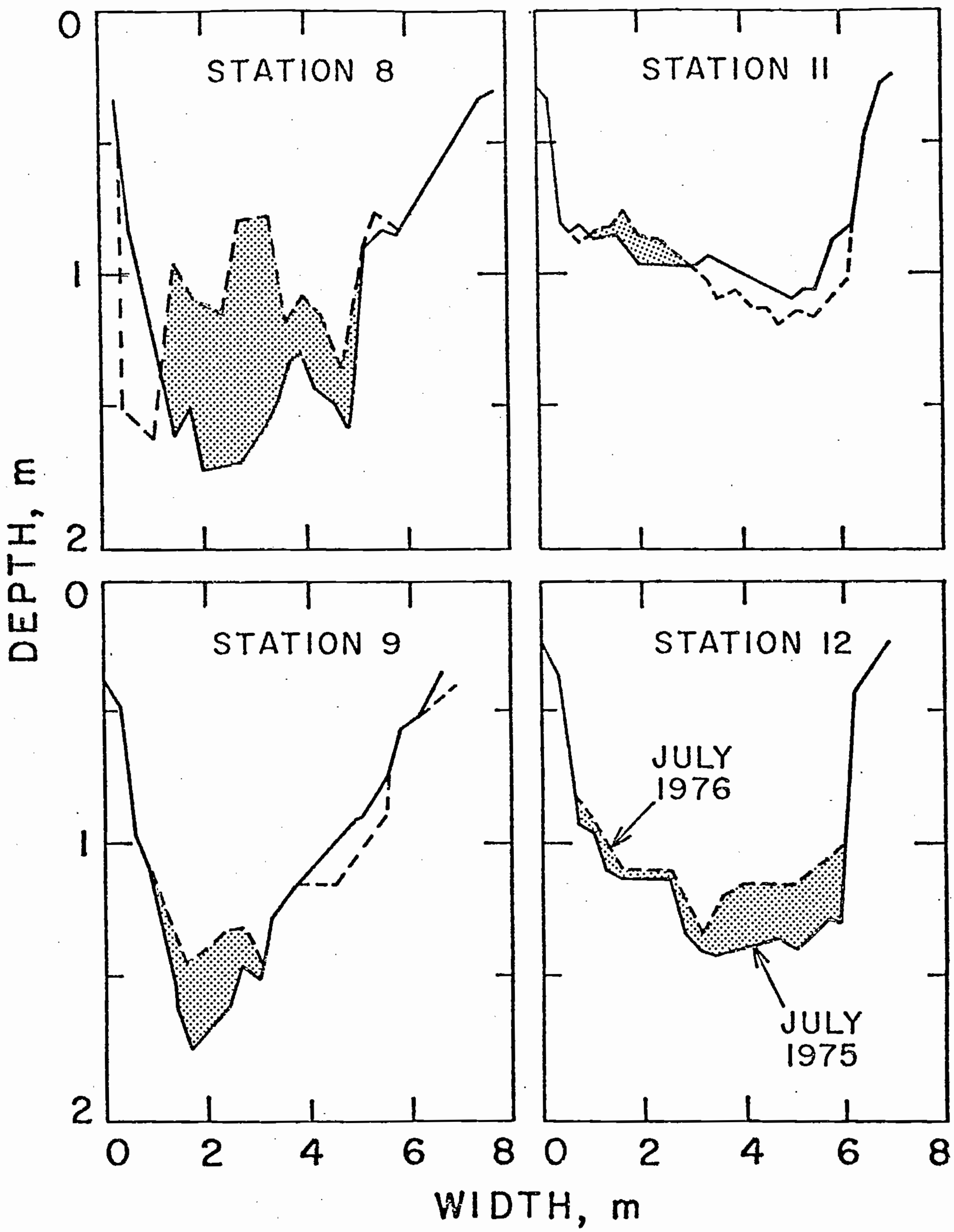

Figure 27. Cross-sectional profiles illustrating net deposition (shaded) and scour (unshaded) for Oak Creek, 1975-76.

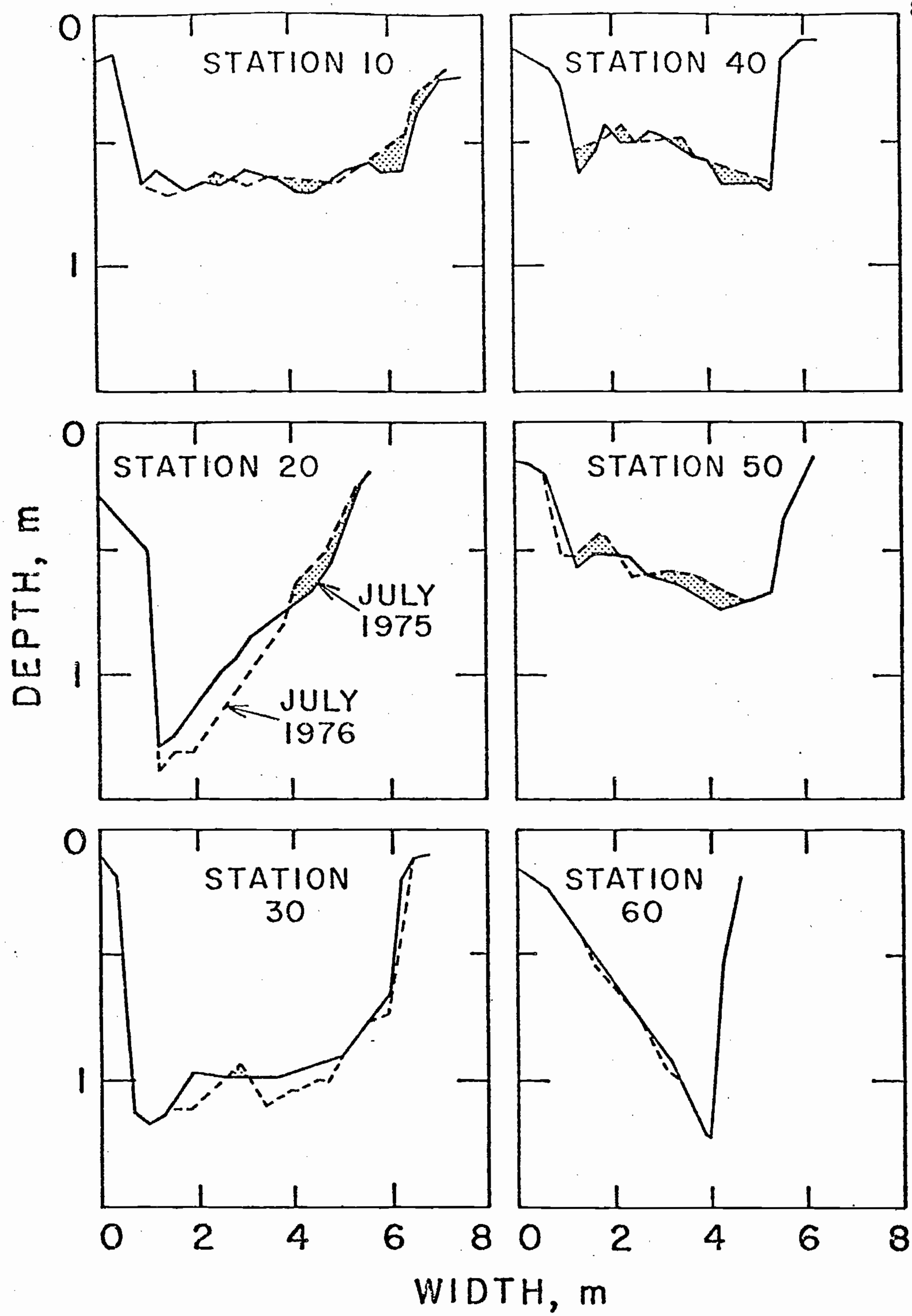

Figure 28. Cross-sectional profiles illustrating net deposition (shaded) and scour (unshaded) for Flynn Creek, 1975-76.

Scour chains were installed at each profile station in both streams in hopes of determining the maximum depth of scour and the depth of backfill at each channel cross section for the year. The large size of bed cobbles made excavation and measurements of the scour chains particularly difficult in Oak Creek. In addition, many of the chains were either washed out or deeply buried in the bed. As a result of the low recovery rate and the difficulty of accurately "reading" the chains, results were inconclusive for Oak Creek.

Useful results were obtained for Flynn Creek, however. A mean depth of scour of 0.04 m and depth of fill of 0.08 m were calculated for stations 10 through 60. This would seem to indicate a general bed disturbance during one or more of the high flow events. In most sections the stream bed returned to nearly the same configuration.

Bed gravel samples were taken in October 1976, just prior to the normal high runoff period, in order to estimate the total amount of fine sediment readily available in the bed gravels. Mean channel widths and average depths of disturbance were estimated from the information obtained at the channel profile stations. Channel lengths were measured from topographic maps. The results are summarized in Table 5 . Fine sediment storage in the bed is approximately 55,000 kg for Oak Creek and 12,500 kg for Flynn Creek. It is interesting to compare this information with sediment yield data from the previous winter. The estimated yield for Oak Creek during 1976 was 180,000 kg. The calculated fine sediment stored in the bed represents 30% of this total. For Flynn Creek an estimated 130,000 kg of sediment was transported and in this case the fine sediment stored in the bed represents only 10% of the total. These results may indicate that the bed fines reservoir plays a more significant role in the sediment regime of Oak Creek than it does in the sediment regime of Flynn Creek.

Table 5. Bed fines analyses, Flynn and Oak creeks, 1975-76.

Stream order	Channel width (m)		Channel length (m)		Depth of disturbance (m)		Suspended sediment concentration in gravels ($kg \cdot m^{-3}$)		Total wt. (kg)
					Oak Creek				
3 & 4	4	x	4389	x	.15	x	20.92	=	55,091
					Flynn Creek				
2 & 3	4.3	x	3219	x	.125	x	7.2	=	12,457

SUMMARY AND CONCLUSIONS

Several aspects of suspended sediment transport in two small, Oregon Coast Range watersheds have been investigated. Major facets of the study included the evaluation of sampling methodology and measurement techniques for determining sediment concentration, the evaluation of temporal variability in SSC, and the identification of potential in-channel sources of fine sediments.

Measurements taken at the Oak Creek study site indicate that no significant horizontal gradation of suspended sediment load occurs. A comparison of DH 48 depth integrated sediment samples and point samples taken with the ISCO pumping sampler near the bed of the stream indicates significant vertical suspended sediment concentration gradients in the water column at Oak Creek. This effect is most prominent during high flows, and may be the result of bed load-suspended load interactions.

Two kinds of measurement techniques, i.e., nephelometric and filtration-gravimetric, were used to estimate sediment loads. The correlation between direct measures (gravimetric-filtration) and indirect measures (nephelometry) was found to be high on the Oak Creek watershed. Insufficient data from Flynn Creek prevented a similar comparison.

The temporal variability in SSC as it relates to hydrograph characteristics was the major consideration of this study. Several interrelationships between storm hydrograph characteristics and sediment transport rate were observed. A hysteresis effect was illustrated whereby higher sediment concentrations for a given stream discharge was evident on the rising limb of most storm hydrographs. A decrease in the amount of suspended sediment yield per unit volume of streamflow from the Oak Creek watershed was observed to occur as the winter runoff period progressed. This phenomenon was found to approximate a log-linear function. Both of these effects (in-storm hysteresis and declining sediment yields through the runoff period) are thought to be tied to channel bed movement. The disturbance and formation of the armor layer on these gravel bottomed streams is hypothesized to be a major factor controlling the release of fine sediment stored in the streambed gravels.

An analysis of fine sediment material stored in the bed gravels of Oak Creek and Flynn Creek indicates substantial amounts of suspendable material do exist within the stream gravels. The preliminary results show these in-channel sediment source areas have the potential of supplying 10% to 30% of the suspended load on these streams.

A comparative analysis of the sediment regimes of Oak Creek and Flynn Creek was made using selected soils and geomorphic parameters. Such factors as soil texture, erosivity, runoff potential, and stream channel gradient and stability appear to be useful indices in characterizing the suspended sediment regime of the two study watersheds.

Although sediment concentrations and transport in small mountain streams are variable in both time and space, this study has identified several definite patterns of variation. Concentrations can rapidly change (at a greater relative rate than the hydrograph) and these changes are related to hydrograph characteristics and the history of previous flow events. These results should provide additional insights for sediment transport processes on other mountain watersheds in the Pacific Northwest.

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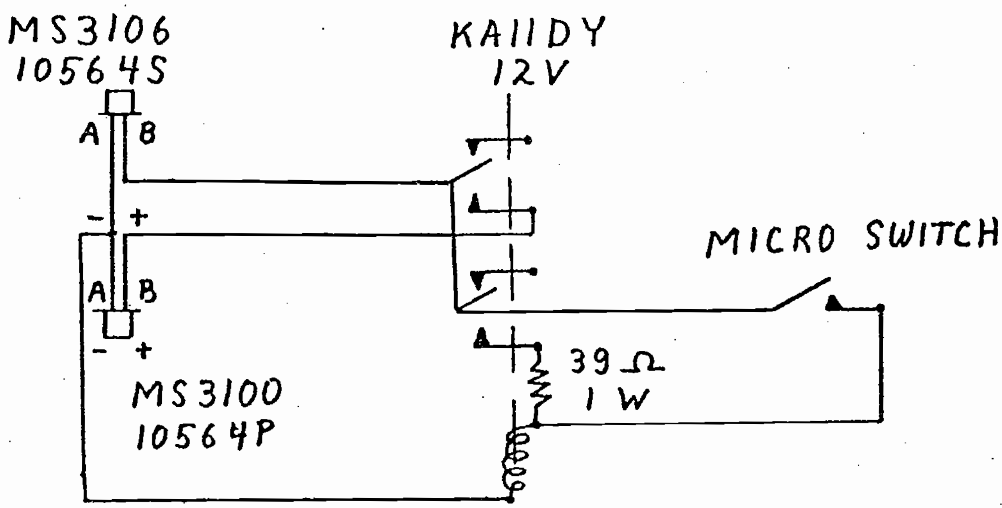
APPENDICES

Schematic Diagram of Magnetic Switching Device Used to Initiate ISCO Pumping Sampler



APPENDIX B

DISCHARGES, SEDIMENT CONCENTRATIONS AND TURBIDITIES FOR STORMS 1-6 AT OAK CREEK, WINTER 1975-76

Key to Appendix B

Column Heading	Column Description
A	Time, 1/2 hour
B[1]	Discharge, $ft^3 \cdot sec^{-1}$
C	Cumulative Discharge, $ft^3 \cdot sec^{-1} \cdot 1/2$ hr
D	Suspended sediment concentration, $mg \cdot l^{-1}$
E	Turbidity, ntu

[1] $(ft^3 \cdot sec^{-1}) \cdot (0.02832) = m^3 \cdot sec^{-1}$

Storm Number	Starting time for data record, i.e. T=0
1	2000 hours on 11-29-75
2	1630 hours on 12-03-75
3	0200 hours on 12-04-75
4	0000 hours on 2-14-76
5	1200 hours on 2-24-76
6	0000 hours on 3-24-76

Storm 1

A	B	C	D	E
14,	1.5,	3.1,	0,	12,
18,	2.2,	5.2,	0,	12,
26,	12.8,	18.0,	480,	0,
37,	46.2,	64.3,	940,	0,
38,	45.3,	109.5,	1200,	0,
38,	44.3,	153.8,	640,	0,
40,	53.4,	207.2,	1320,	0,
41,	63.2,	270.4,	970,	0,
42,	67.9,	338.3,	252,	0,
43,	70.2,	408.5,	127,	0,
44,	70.2,	478.9,	130,	0,
45,	67.9,	546.6,	280,	0,
46,	54.4,	601.1,	352,	0,
47,	54.4,	655.5,	363,	0,
48,	67.9,	723.4,	310,	0,
49,	80.1,	803.5,	292,	0,
50,	90.6,	894.1,	142,	0,
51,	113.3,	1007.4,	217,	0,
54,	72.7,	1080.0,	129,	47,
56,	61.0,	1141.0,	105,	40,
58,	61.0,	1202.0,	80,	40,
60,	65.5,	1267.5,	86,	37,
62,	71.4,	1338.9,	80,	37,
64,	70.2,	1409.2,	137,	35,
66,	70.2,	1479.4,	114,	35,
68,	65.5,	1544.9,	210,	45,
70,	61.0,	1605.9,	137,	48,
72,	56.6,	1662.5,	82,	42,
74,	52.3,	1714.8,	70,	39,
76,	44.3,	1759.1,	69,	33,
78,	40.5,	1799.6,	86,	32,
80,	37.8,	1837.4,	90,	32,
82,	35.2,	1872.6,	0,	33,
84,	31.8,	1904.4,	0,	30,
86,	27.0,	1931.[illegible],	0,	30,
88,	25.5,	1956.9,	0,	28,
90,	23.3,	1980.3,	0,	26,
92,	21.9,	2002.2,	0,	25,
94,	19.9,	2022.1,	0,	25,
96,	19.3,	2041.4,	0,	23,
98,	18.6,	2060.1,	0,	22,
100,	18.0,	2078.1,	0,	22,
102,	17.4,	2095.4,	0,	21,
104,	16.8,	2112.2,	0,	21,
106,	16.2,	2128.4,	0,	20,
108,	15.6,	2143.9,	0,	18,
112,	13.9,	2157.8,	0,	18,
116,	12.3,	2170.1,	0,	17,
118,	12.3,	2182.[illegible],	0,	17,
120,	11.7,	2194.1,	0,	17,
124,	10.7,	2204.8,	0,	15,

Storm 2

A	B	C	D	E
14,	35.2,	41.6,	62,	35,
15,	48.2,	89.8,	115,	50,
16,	58.8,	148.5,	210,	0,
17,	82.7,	231.2,	339,	0,
19,	141.5,	372.6,	449,	0,
20,	151.6,	524.3,	775,	0,
21,	161.9,	686.3,	465,	0,
22,	161.9,	848.2,	519,	0,
23,	149.9,	998.1,	529,	0,
24,	141.5,	1139.6,	560,	0,
25,	119.3,	1259.0,	535,	0,
26,	110.3,	1369.3,	546,	0,
27,	96.0,	1465.3,	312,	0,
28,	93.3,	1558.6,	269,	0,
29,	82.7,	1641.3,	429,	0,
30,	90.6,	1731.9,	232,	0,
31,	72.7,	1804.5,	157,	0,
32,	65.5,	1870.1,	182,	0,
33,	61.0,	1931.0,	157,	0,
35,	58.8,	2050.3,	82,	44,
36,	54.4,	2105.2,	117,	46,
37,	52.3,	2157.5,	184,	43,
38,	48.2,	2205.8,	88,	38,
39,	48.2,	2254.0,	0,	37,
40,	40.5,	2294.5,	0,	35,
41,	36.9,	2331.4,	0,	35,
42,	36.0,	2367.4,	0,	35,
44,	33.5,	2400.9,	0,	32,
46,	31.0,	2431.9,	0,	34,
48,	30.2,	2462.0,	0,	30,
50,	27.0,	2489.0,	0,	30,
52,	24.1,	2513.1,	0,	25,
54,	23.3,	2535.5,	0,	30,
56,	22.6,	2559.1,	0,	28,
58,	21.3,	2580.4,	0,	25,
60,	19.9,	2600.3,	0,	25,
62,	19.3,	2619.6,	0,	22,
64,	19.3,	2638.8,	0,	22,
66,	18.0,	2656.8,	0,	24,
68,	17.4,	2674.2,	0,	21,

Storm 3

A	B	C	D	E
12,	13.3,	18.3,	0,	24,
14,	16.2,	34.5,	56,	47,
16,	17.4,	51.8,	59,	50,
17,	18.0,	69.8,	277,	0,
21,	28.6,	98.4,	195,	0,
25,	48.2,	146.6,	170,	0,
29,	62.1,	208.7,	59,	0,
33,	46.2,	255.0,	45,	46,
37,	40.5,	295.5,	36,	40,
41,	38.7,	334.2,	36,	30,
46,	33.5,	367.7,	41,	35,
49,	31.0,	398.6,	29,	27,
53,	27.8,	426.4,	29,	28,
57,	25.5,	451.9,	25,	26,
61,	27.0,	479.0,	26,	24,
65,	28.6,	507.5,	19,	24,
69,	27.0,	534.6,	20,	23,
71,	24.8,	559.4,	22,	30,
77,	22.6,	582.0,	32,	24,
81,	22.6,	604.7,	23,	24,
85,	28.6,	633.2,	15,	22,
89,	30.2,	663.4,	17,	22,
93,	28.6,	692.0,	26,	21,
96,	27.8,	719.8,	31,	23,
103,	26.3,	746.0,	35,	22,
115,	20.6,	766.6,	6,	21,
123,	19.9,	786.5,	16,	20,
127,	18.6,	805.2,	16,	20,
139,	21.3,	826.4,	9,	24,
151,	34.3,	860.7,	31,	35,
161,	61.0,	921.7,	140,	70,
162,	65.5,	987.2,	180,	82,
164,	104.5,	1091.8,	306,	120,
165,	122.4,	1214.1,	256,	125,
166,	138.3,	1352.4,	273,	140,
167,	153.3,	1505.7,	286,	132,
168,	148.2,	1653.9,	221,	120,
169,	135.0,	1788.9,	266,	108,
170,	128.6,	1917.5,	116,	96,
171,	116.3,	2033.8,	115,	70,
172,	107.4,	2141.2,	105,	64,
173,	101.6,	2242.9,	89,	62,
176,	85.3,	2328.1,	81,	60,
177,	87.9,	2416.1,	68,	54,
178,	93.3,	2509.4,	70,	56,

Storm 3 (continued)

A	B	C	D	E
179,	93.3,	2602.7,	64,	55,
180,	87.9,	2690.6,	59,	48,
181,	87.9,	2778.5,	65,	40,
182,	85.3,	2863.8,	45,	35,
183,	82.7,	2946.4,	50,	36,
184,	82.7,	3029.1,	57,	36,
185,	90.6,	3119.7,	47,	44,
186,	101.6,	3221.3,	74,	44,
187,	110.3,	3331.7,	107,	60,
188,	123.9,	3455.6,	101,	70,
189,	116.3,	3571.9,	113,	65,
190,	110.3,	3682.2,	98,	60,
191,	98.8,	3781.0,	81,	50,
192,	93.3,	3874.3,	78,	50,
193,	90.6,	3964.9,	60,	51,
194,	87.9,	4052.8,	54,	50,
195,	85.3,	4138.1,	53,	37,
196,	82.7,	4220.8,	45,	38,
197,	77.6,	4298.4,	47,	35,
198,	72.7,	4371.0,	39,	34,
199,	70.2,	4441.3,	37,	33,
200,	65.5,	4506.8,	43,	32,
201,	64.4,	4571.2,	24,	30,
202,	63.2,	4634.4,	29,	29,
203,	61.0,	4695.4,	21,	30,
212,	48.2,	4743.6,	26,	26,
214,	46.2,	4789.9,	17,	24,
216,	44.3,	4834.2,	13,	22,
218,	42.4,	4876.6,	14,	23,
220,	40.5,	4917.1,	16,	20,
222,	40.5,	4957.6,	0,	23,
224,	38.7,	4996.3,	0,	20,
226,	36.9,	5033.2,	0,	22,
228,	36.0,	5069.2,	0,	22,
230,	35.2,	5104.4,	0,	22,
232,	33.5,	5137.8,	0,	21,
234,	32.6,	5170.4,	0,	20,

Storm 4

A	B	C	D	E
10,	1.0,	1.5,	0,	15,
22,	1.0,	2.5,	0,	16,
34,	1.0,	3.5,	0,	16,
46,	1.0,	4.5,	0,	15,
58,	0.9,	5.4,	0,	15,
70,	0.9,	6.2,	0,	15,
82,	1.0,	7.2,	0,	16,
94,	3.2,	10.4,	30,	30,
106,	9.8,	20.2,	103,	70,
118,	15.6,	35.8,	60,	60,
130,	13.9,	49.6,	37,	43,
142,	10.7,	60.4,	12,	38,
149,	9.8,	70.2,	9,	35,
154,	8.9,	79.1,	12,	32,
158,	8.4,	87.5,	28,	30,
162,	8.4,	95.9,	11,	28,
166,	9.8,	105.7,	12,	30,
170,	15.0,	120.7,	29,	37,
172,	17.4,	138.1,	52,	40,
177,	15.0,	153.1,	26,	39,
181,	13.9,	167.0,	18,	36,
185,	13.3,	180.3,	19,	35,
190,	12.3,	192.6,	17,	33,
193,	11.7,	204.3,	14,	31,
197,	10.7,	215.1,	12,	30,
201,	10.3,	225.3,	13,	30,
205,	9.8,	235.1,	0,	27,
210,	8.9,	244.0,	0,	26,
212,	8.9,	252.9,	0,	25,
218,	8.0,	260.9,	0,	31,
222,	7.6,	268.5,	0,	28,
226,	7.6,	276.1,	0,	26,
230,	7.2,	283.3,	0,	25,
234,	7.2,	290.5,	0,	25,

Storm 5

A	B	C	D	E
4,	25.5,	34.4,	98,	84,
7,	65.5,	99.9,	264,	170,
9,	80.1,	180.1,	316,	148,
11,	104.5,	284.6,	250,	128,
13,	122.4,	406.9,	275,	130,
15,	131.8,	538.8,	225,	120,
17,	135.0,	673.8,	249,	105,
19,	161.9,	835.7,	212,	100,
21,	135.0,	970.7,	226,	110,
23,	101.6,	1072.4,	153,	88,
25,	90.6,	1163.0,	119,	80,
27,	98.8,	1261.8,	96,	68,
29,	70.2,	1332.0,	65,	60,
31,	65.5,	1397.6,	53,	60,
33,	61.0,	1458.5,	45,	48,
35,	58.8,	1517.3,	44,	48,
37,	56.6,	1573.9,	38,	45,
39,	52.3,	1626.2,	36,	40,
41,	50.3,	1676.4,	20,	33,
44,	46.2,	1722.7,	0,	28,
48,	40.5,	1763.2,	0,	27,
52,	35.2,	1798.4,	0,	25,
54,	34.3,	1832.7,	0,	23,
56,	32.6,	1865.3,	0,	22,
58,	31.8,	1897.1,	0,	27,
60,	31.8,	1928.8,	0,	33,
64,	46.2,	1975.1,	0,	32,
70,	54.4,	2029.5,	0,	33,
71,	58.8,	2088.3,	22,	34,
73,	63.2,	2151.5,	34,	36,
75,	70.2,	2221.7,	48,	37,
77,	72.7,	2294.4,	44,	43,
79,	65.5,	2359.9,	23,	35,
81,	58.8,	2418.7,	30,	35,
83,	52.3,	2471.0,	25,	35,
85,	52.3,	2523.3,	21,	30,
87,	51.3,	2574.6,	0,	31,
92,	44.3,	2618.9,	0,	30,
96,	38.7,	2657.6,	0,	27,
102,	40.5,	2698.1,	0,	27,
108,	38.7,	2736.8,	0,	25,
114,	37.8,	2774.6,	0,	22,
120,	35.2,	2809.8,	0,	21,
126,	38.7,	2848.5,	0,	22,
132,	38.7,	2887.1,	0,	22,
136,	50.3,	2937.4,	0,	28,
139,	66.7,	3004.1,	88,	45,
141,	80.1,	3084.2,	105,	70,
143,	80.1,	3164.3,	92,	60,
145,	80.1,	3244.4,	64,	45,
147,	77.6,	3322.0,	46,	40,

Storm 5 (continued)

A	B	C	D	E
149,	75.1,	3397.1,	38,	37,
151,	64.4,	3461.5,	40,	34,
153,	63.2,	3524.7,	40,	32,
155,	52.3,	3577.1,	38,	31,
161,	39.6,	3616.7,	31,	28,
173,	35.2,	3651.8,	0,	25,
185,	28.6,	3680.4,	0,	22,
197,	27.8,	3708.2,	0,	22,

Storm 6

A	B	C	D	E
16,	65.5,	71.9,	139,	110,
30,	54.4,	126.4,	0,	60,
32,	48.2,	174.6,	60,	50,
34,	44.3,	218.9,	30,	50,
36,	41.5,	260.3,	41,	45,
38,	38.7,	299.0,	23,	40,
40,	36.9,	335.9,	18,	37,
42,	36.9,	372.8,	22,	35,
44,	36.0,	408.9,	20,	35,
46,	35.2,	444.0,	18,	34,
48,	33.5,	477.5,	24,	33,
50,	33.5,	510.9,	19,	32,
52,	31.8,	542.7,	17,	32,
54,	31.8,	574.5,	23,	31,
56,	31.0,	605.5,	16,	32,
58,	31.8,	637.3,	18,	31,
60,	30.2,	667.4,	16,	30,
62,	30.2,	697.6,	18,	31,
64,	29.4,	726.9,	24,	29,
66,	28.6,	755.5,	13,	29,
68,	27.0,	782.5,	0,	30,
70,	26.3,	808.8,	0,	28,
72,	25.5,	834.3,	0,	27,
74,	25.5,	859.9,	0,	26,
76,	24.1,	883.9,	0,	26,
78,	23.3,	907.3,	0,	25,
80,	22.6,	929.9,	0,	25,
82,	21.3,	951.2,	0,	25,